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Cement Bond Evaluation

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MASTER'S THESIS
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Preface

The work of this thesis was carried out at Halliburton's facility at Tananger, Norway. I want to thank Halliburton for earlier employment and for giving me the opportunity for thesis work.

I would like to thank my supervisor at Halliburton, Silje Arnesen, for excellent guidance throughout the work process and for sharing your knowledge along the way.

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I would further like to thank fellow colleagues from Halliburton's Fluids Laboratory whom I have had the great pleasure of working with for three years. I would also like to thank future colleagues at the Cementing Department for interesting input during my thesis work and for including me in their work day.

In addition, I would like to thank fellow students and friends from my five year stay at the University of Stavanger for all the memories we are so lucky to share.

And finally, a very special thanks to my closest family for their much appreciated and continuous support.

Abstract

As part of completing an oil well strings of casing are inserted into a pre-drilled hole and cemented in place. The twofold purpose of the cement is to provide casing support and hydraulically isolate the annular space to avoid unwanted communication between zones. To establish whether or not a cemented interval meets given requirements, logging tools are run downhole to yield data that allow subsequent cement evaluation. In later years, however, many cement jobs executed according to best practices have been logged and deemed unsuccessful while further jobs done in the same way under similar well conditions have been judged differently, with no apparent logical explanation. Industry today does not know for sure whether the discrepancies are caused by job execution, cement as annular material, formation properties, or logging techniques. Cement that fail to be deemed as successful well barrier is a costly problem and effort should hence be allocated to find a solution. This thesis has in co-operation with Halliburton approached the problem and investigated 38 jobs. The aim for the thesis work is to look for any trends that can help pinpoint the root cause, or causes. The thesis approaches previous research together with common industry practice and employ the knowledge of both into a troubleshooting process that includes case studies and a statistical survey. The work has demonstrated the applicability of such statistical approach, but the sample size needs to be of more considerable size in order to cope with the complexity of the problem. Non-conventional cement design and high density drilling fluids are found to continuously be involved in troublesome cases, but the sample size is considered to be too small for being more conclusive.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

Hydrocarbons are produced through oil wells which are the combined result of a drilled hole and its inserted production equipment of various sorts. When the well is to be completed, whether it is located offshore or onshore, sections of steel pipe called casing are inserted into the drilled hole and cemented in place. When a cement job is completed it is necessary to verify if the job can be deemed successful, i.e. whether or not there is circumferential cement coverage of the pipe that meets the prevailing requirements of the particular section. The purpose of cement is to provide support to the casing but also to prohibit fluid flow in the annular space between the outside of the casing and the inside of the wellbore. This circumferential cement coverage, commonly referred to as the cement sheath, is evaluated based on data obtained from cement evaluation logs that utilize sonic and ultrasonic measurement techniques. For the owner of the well it is important to know where there is good cement behind pipe and if zonal isolation can be expected so that they can perforate and start production accordingly.

Oil industry on the Norwegian Continental Shelf (NCS) are experiencing one too many logs that does not agree with the anticipated outcome of the cement job. This is a costly problem in need of immediate attention, and the purpose of this thesis is to investigate jobs where the execution parameters suggest better results than provided by the logs. The goal is to look for plausible reasons to the experienced discrepancies to help find a solution to the problem. The topic has been approached by several beforehand and numerous papers have been published addressing both specific and general challenges. This thesis has studied some of these papers and a summary of their findings are given. Further, in order for the thesis to be self-contained, it includes basic theory of cementing- and logging techniques including critical parameters and areas of concern.

The thesis has investigated cementing jobs performed by Halliburton on the NCS during the period (2010-2014) with logging operations ran either by Halliburton, Schlumberger or Baker Hughes. The cement jobs investigated are primary cement jobs that place cement in the annular space between the casing pipe and the formation wall in the wellbore, or between two concentric casing strings. Essential parameters for each job have been plotted against each other in order to look for repeatability and patterns, and selected jobs have been studied in more detail to try and identify any explanation to the experienced mismatches. The thesis also demonstrates how job execution parameters from cementing operations can be used as input to the Halliburton software modelling program iCem® so that the job can be simulated and plausible scenarios compared. Additionally, as part of the thesis, a 2-week Cement and Casing Evaluation Course held by Halliburton in Houston was completed. The course provided up-to-date information on best work practice and interpretation of the logs used for cement evaluation. Trough presentations and discussions, common logging issues were addressed such as for instance the challenges related to non-conventional slurry designs. Knowledge and statements from the seminar are integrated in the thesis and some of the issues are discussed towards the end.

2.0 Literature Review

Discrepancy between log result and anticipated job outcome is far from a novel problem. Research on cement evaluation techniques including improvement methods and recommended guidelines has been carried out for decades, but still some log results are being questioned. Analyses and experiments that study critical factors and relationships have been directed to approach the challenges related to cement evaluation. Overall, the published work agrees heavily on the very existence of the problem and their concluding remarks are used as a joint anchor point for observations made during the case study contained later in this thesis.

There is little doubt that previous research has contributed to a better understating of cement evaluation since the CBL first were introduced in the late 50's and early 60's. Already from the beginning research was carried out to enhance the understanding of the cement logs, and early papers [1] demonstrated the delicacy of bond logs and how the interpretation of them required knowledge of instrument sensitivity, cement properties, hole size, formation, and the prevailing temperature and pressure regimes during cement curing. These topics and new ones have on numerous occasions been addressed though time from jointly perspectives [2, 3] and by means of more acute studies on the influence from, i.a., *borehole geometry* (cement thickness, stand-off, displacement efficiency and channels) [4], *formation* [5, 6], *borehole fluid* [7, 8], *slurry design* [9–11], and *deviated wells* [12]. External and physical parameters are not the only area to raise concern and measurement principles, log presentations, and log interpretations are other areas that have been subject to questioning and subsequent research. Below follows a brief recap on the main findings from some selected studies.

A study in 1994[13] critically addressed the Bond Index (BI), which at the time was the only method that gave a quantitatively evaluation of the cement job. Through experiments and case studies the research of concluded that the conventional BI should be abandoned for being derived on false basis and yielding unexplainable results during studies with known conditions. The same experiments failed to reproduce the proposed logarithmic relationship of the BI, but rather yielded a linear relationship which they later used as basis for a new measure called Bond Percentage Index (BPI)[13]. A more recent paper (2013)[12] presents guidelines for how to avoid misinterpretation of log data and consequently to ameliorate the final results during cement evaluation in horizontal wells. The same paper emphasizes on which information is important to the interpretation process and how the information needs to be made utilizable for people involved in the process. Further, the paper lists common misconceptions and typical interpretation mistakes when it comes to cement evaluation, all which are of great importance to the content of this thesis. Another paper (2012)[14] underlines the complexity of CBL measurements and hence how important it is that log data are interpreted by highly skilled personnel that are able to grasp this very complexity. The concluding remarks of the paper coincide with what the author has experienced to be a fundamental source of insecurity, namely the extremely composite and complicated nature of log interpretation.

Work of more comprehensive nature (2008)[15] deal with the overall reliability of cement evaluation where the log interpretation are judged based on their correspondence to physical communication tests (between zones). The focus area is the total ability to evaluate whether or not hydraulic isolation is present behind the casing based on the logs, which really is one of the major questions being asked in the industry and also the background for this thesis. Out of twenty-eight examined wells, the interpretation of twenty-five logs were considered to fit the physical test; one log gave mismatch but with tool eccentricity problem as reason; while the last two interpretations failed to reveal the presence of communication behind the casing - without yielding any definitive explanation to the mismatch. In fact, the bond log indicated excellent cement quality even though full communication was achieved during physical tests. The match to mismatch ratio for the survey was equal to 89%[15] which may or may not be argued as sufficient with respect to reliability. However, what really impair the results of the survey are the two anomalous cases where a clear mismatch between log interpretation and physical tests occurred. The lack of one clear explanation to such experienced problems contributes to insecurity and subsequent mistrust in log results. The study[15] suggests mud contamination of the cement and how it can impair the log data by increasing the thickening time, lowering the compressive strength, and reducing the impedance contrast between cement and fluid.

More papers are available on cement evaluation and it also reasonable to believe that investigations of more internal character are carried out in the industry; and if not, attention should be directed to the topic. Bond logs are a time saving method as opposed to the physical communication tests [15] and are hence more economical to use. However, interpretation reliability is an essential part of whether or not the method can be seen as cost efficient because of the high costs associated with remedial jobs and other repair work caused by inaccurate log results. The reliability study [15] performed simple calculations that yielded a *break even failure rate* of 10-11% out of the total number of drilled wells, i.e. the reliability for logs to identify communication must exceed 89-90% in order to be economic. The calculations will not be elaborated any further, but it should be mentioned that it was based on relatively simple estimates and the assumption that the need for a remedial job was discovered a certain time after the drilling rig had left location. However, such derived number can nevertheless be used to reflect the significant cost associated with remedial jobs and hence to underline the importance of being able to trust log data and interpretation.

The reviewed papers correspond well with each other when describing the problem at stake. Different approaches are taken and some concern areas have been highlighted and their extent confirmed by research and experiments. However, there are still a lot of unanswered questions within the field of cement evaluation, and they continue being discussed as anomalous log results arise from the cemented wells. Among the studies there is a mutual agreement on complexity in log interpretation and how cement evaluation requires a composite approach involving all relevant data. Flattening production levels and increased operating costs impose challenges to the oil industry which in turn must struggle to keep the bottom line low. Being able to accurately evaluate the cement job and quickly move on to the next completion stage with confidence in the cement job is crucial to avoid non-productive-time and thus to minimize operational costs. Cement evaluation hence induce a considerable economic aspect that justifies further research.

3.0 Well Structure and Cementing

3.1 The Drilling Process

To bring hydrocarbons to the surface in a safe and profitable way there are several processes that must be successfully carried out by the respective oil and service companies. Once an oil well is drilled, casing is inserted into the hole to protect the well from rock debris falling into it and even from total formation collapse. Casing is a steel pipe that is cemented in place by pumping cement slurry down through the casing and up the annular space between the outside of the pipe and its immediate surrounding which can be either the wellbore or a larger diameter pipe. A plug called the bottom plug is released immediately ahead of the slurry and forced down the casing by the pressure from the cement pumps. When the plug stops in the float collar the continued pressure from the cement pumps opens a passageway through the plug allowing the slurry to proceed down the casing, out the opening in the guide shoe and finally up the annular space. A plug called the top plug is released after the last cement slurry enters the casing, and a displacement fluid (usually water or drilling mud) is pumped in behind the top plug to push the remaining slurry out in the annular space. The top plug eventually seats on the bottom plug and sufficient waiting time is given to allow the cement slurry to solidify; a period of time often referred to as WOC (Wait on Cement).

There are four basic types of casing strings to be run in a well depending on well depths, formations, pressures, temperature, freshwater zones, and fluid type to be recovered. *Conductor casing* is used if the uppermost section of the subsurface consists of poorly consolidated and easily erodible soil. The conductor casing usually has a large Outside Diameter (OD) (16" to 36".) and it is either drilled down or piled into the subsurface until it reaches solid material, normally 90 to 150ft (possibly as shallow as 10ft and rarely deeper than 300ft). Cement is only used around conductors ran in pre-drilled holes. *Surface casing* is the second string set in a well unless conductor casing is not used (then the surface casing will be the first). The surface casing is designed to protect shallow formations from deeper drilling conditions, like for instance to prevent fresh water zones from being contaminated by drilling fluids and/or produced fluids. The surface casing is cemented back to the surface (or seabed[1]) to provide both a cement sheath and a steel surface to protect freshwater zones. The size of the surface casing ranges from 7-5/8" to 20" OD depending on several well parameters like depth, pressure, temperature, and fluid properties. *Intermediate casing* is set after the surface casing and is also referred to as *protective casing*. This casing string is designed to withstand the pressure from a *kick*, which is the case where the subsurface pressure becomes higher than the mud weight allowing formation-to-wellbore fluid flow. In this manner the protective casing provides hole integrity during later drilling operations, but it also protects the formations behind the casing from high mud weights which can fracture the rocks. The size depends on the same well parameters as for the surface casing, but it usually ranges from 6 5/8" to 20" and is usually cemented up to about 200-400 meters above the casing shoe, preferably in multiple stages for significant depths or if the formation is fragile. *Production casing* is the final full string of pipe that is set in the well. The most common sizes for production casings are 9-5/8" and 9-7/8" OD and they are often followed by a 7" or a 5-1/2" *liner*, respectively. A *liner* is a string of steel pipe that is hung from the bottom of the previous cemented casing string. The technique

[1]Offshore wells, including every well on the NCS, are cemented back to seabed

is advantageous and saves both time and money since it does not require the pipe to extend all the way from the reservoir to the surface (or seabed). Because this final string is set in the production zone and cemented in place it must be perforated prior to production start-up and the quality of the cement for this casing is thus crucial for the success of the well. *Perforations* are holes that are made through the casing, the cement sheath, and some additional distance into the reservoir formation to provide a path for reservoir fluids to flow from the formation (and into the production tubing which provides a smooth bore back to the production unit at surface). Perforations are usually done by lowering a tool consisting of shaped-charged explosives into the well (opposite of the producing zone) and discharged electronically from the surface. The *production tubing* is run into the casing in conjunction with a *production packer* to seal off the outside of the tubing. The purpose of the tubing is to protect the casing from wear, tear, and corrosion caused by formation fluids. The tubing will also protect the casing from from undesirable deposition of sands, paraffins, and asphaltenes. It is further more feasible to replace a worn-out tubing compared to a casing that is cemented in place.

3.2 Primary Cementing Techniques

Primary cementing is the operation where cement slurry is placed in the annular space between the casing and borehole wall in order to provide support for the pipe and to provide hydraulic isolation. It is a critical operation for the success of the well and careful planning and execution is thus necessary, especially near the production zones. The cementing technique applied for different types of casing strings are principally the same though certain variations in casing details and/or well parameters may impose some difference to each operation. Slurry design, mud conditioning, spacer volume, pipe movement, and displacement rate are typical factors that will change with operating conditions in order to optimize the displacement efficiency and they will be addressed in more detail later. Below follows a brief description of two common cement placement techniques.

Cementing Through Drillpipe (*Stab-in* or *Inner-string* cementing)

When the *stab-in* technique is used the casing is first run in place with a stab-in float shoe and casing slips are used to suspend the casing string off bottom [11]. A stab-in stinger is run in the casing and placed approximately three feet above the float shoe, drilling mud is then circulated before the stinger is lowered and screwed (stabbed) into the float shoe. A spacer fluid is usually pumped ahead of the cement slurry, and both fluids move down through the stringer and are displaced up the annulus and back to the surface. This technique is advantageous in several ways including the fact that there is no need for calculating accurate hole volumes because the slurry is simply pumped until returns are observed at the surface. For casings that are not to be cemented back to surface, a calculated volume plus excess volume is pumped. When sufficient slurry volumes have been pumped the mixing is stopped and the top plug is launched to displace the slurry in the drill pipe. The greatest risk when running stab-in cementing operations is collapsing the pipe due to a blockage in the annular space outside the casing, but on the other hand it eliminates the need for large-diameter *swages*[1] or cement heads, as well as the need for large casing wiper plugs [11]. The limitation with the stab-in technique is that it can only be used on stationary rigs,

[1] Crossover joint to connect two components (casings) with different threading or size

i.e. land rigs, jack-ups, or platform rigs. The *inner-string* cementing technique can on the other hand be executed from both floating and stationary rigs and it also reduces the possibility of casing collapse because equal pressures exist on the inside and outside of the pipe. The inner-string technique utilizes a *cementing mandrel*[1] with the drill pipe hanging freely within to 15 to 30 feet of the casing shoe or collar. For a floating rig the drill pipe is hung of from the conductor- (or surface-) wellhead-housing running tool [11]. A disadvantage with inner-string cementing is that the displacement volume will be rather small which will affect the displacement rate. Most of the cement will be displaced simultaneously as mixing and pumping take place at surface, which means that the displacement rate is dependent on the mixing rate and not the pump rate. Reduced displacement rate is unfortunate to final displacement efficiency, and hence to the final result of the job.

Grouting (*top-up* cementing)

The principle of this method is to pump the cement slurry via a small diameter tubing (common size is 1-7/8") and down into the annulus between the casing and the open hole. The tubing is pushed as far as possible down the annulus before it is connected to the cementing unit by a high pressure treating line [11] and drilling fluid circulation is established. When sufficient volumes are circulated the cement slurry is mixed and pumped only until the slurry is circulated back to the surface. Top-up cementing is applicable when lost circulation occurs during large-casing slurry displacements. There is unfortunately no method to determine how well the cement is being displaced down the annulus. Further, the small diameter of the pipe will impose large friction pressures so care must be taken when pumping. Small diameter tubing is more difficult to use offshore than onshore and a special tool called a Titus Assembly is thus run as a contingency measure together with the casing [11], which allows for top-up cementing of offshore wells.

3.3 Cement Job Design

3.3.1 Prerequisites for a good cement job

For every cement operation there is a set of objectives that must be considered for the job design, including technical challenges, economic aspects, and local regulations. Because the focus of this thesis lies with the connection between executed cementing jobs, log operations, and log evaluation of cement jobs, it will primarily discuss technical aspects. However, a job must nevertheless comply with prevailing regulations, and when it comes to economic considerations they will seldom be excluded from the decision making. Regulative and economical aspects are hence considered and approached on a simple level.

In order for the cement to fulfill the technical objectives, whether it is a simple “fill-up” criteria or a more sophisticated isolation job, there are three basic types of well data that must be considered: 1) *depth and dimensional data*, 2) *wellbore environment*, including pressure regime and drilling fluid engineering, and 3) *temperature regime* [11]. The three categories listed here are all related to conditions at the time of drilling, but because one of the main objectives of well cementing is to provide zonal isolation *throughout* the expected lifetime of the well, one must

[1] Spindle of specialized tubular components for cementing

also consider factors that may compromise the cement sheath in the future. Any lack of considering these parameters for the primary cement job can result in costly remedial jobs to re-achieve well integrity. *Placement techniques* is another area crucial to the success of a cement job and it involves mud removal and casing centralization. The following four subsections summarize the most important elements to consider for cement job design. For more detailed reading and further references the author would like to refer to chapter 5 and 12 in "Well Cementing", published by Schlumberger[11]. A common term to describe the cement job is *Displacement Efficiency*which is defined as the ratio between the cemented area and the total annular space around the casing, as illustrated in Figure 1.

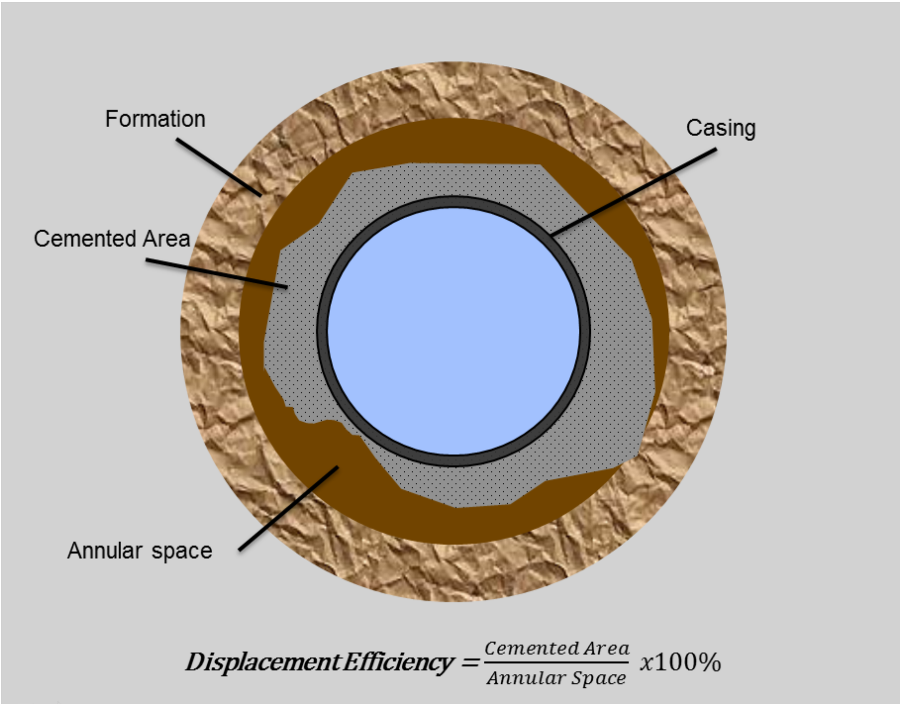

Figure 1: Cross-section of well showing *displacement efficiency* (modified after [16])

3.3.2 Depth and Dimensional Data

The well data that must be gathered when planning a primary cement job includes:

- vertical depth
- measured depth
- angles and azimuths of deviation
- openhole size
- casing size and weight
- string type (e.g. full string, liner, tieback, or multistage)

Depth data are of particular importance as they strongly influence other important parameters such as temperature, pressures, and fluid volume. The eccentricity of the pipe in the borehole is crucial for the mud removal process which again affects the quality of the cementing job. What is important to realize is that a borehole is seldom exactly vertical [11] and unless the exact borehole trajectory is known the inserted casing, which is relatively flexible, may touch the borehole wall as the borehole twist and turn in various directions. Whenever the casing fails to be centered in the borehole the one side will naturally be closer to the wellbore wall on the one side (low side) and further away on the opposite side (high side). The annular space will consequently be reduced on the low side of the well and increased on the opposite high side. This is unfavorable to the low side of the well as the cement slurry being pumped behaves as a fluid and will thus follow the path of least resistance, i.e. one will experience problems with moving cement up the annular space on the low side of the well. The percentage deviation from being centered in the hole is commonly referred to as *standoff*, and is defined as the ratio in percent between actual annular clearance and the annular clearance when the casing is concentric with the wellbore, as illustrated in Figure 2. So 0% standoff means the casing is touching the wellbore wall while 100% standoff is equivalent to a perfectly centered casing, and it is hence preferable to obtain a high as possible standoff. Centralizers are installed on the outside of the casing to force the casing toward the center of the wellbore, and the *amount*, *physical properties*, and *placement* of the centralizers are all vital to the final standoff. Note that casing pipe has the ability to bend between centralizers so the standoff at the centralizers can be high while the standoff in between is low. Sufficient trajectory data can be obtained by seismic surveys (detailed directional survey or 3D survey) or by measurements during the drilling operation (MWD or LWD[1]). If data are unavailable, a minimum deviation of a few degrees (usually 3°) or randomization techniques can be applied to account for trajectory uncertainties. Note that *deviation* is the angle the wellbore deviates from the vertical, while *standoff* is a measure of eccentricity between the casing and the wellbore. The two are, however, related as a deviated well usually pose more challenges with respect to standoff because the efficiency of gravity will increase with deviation.

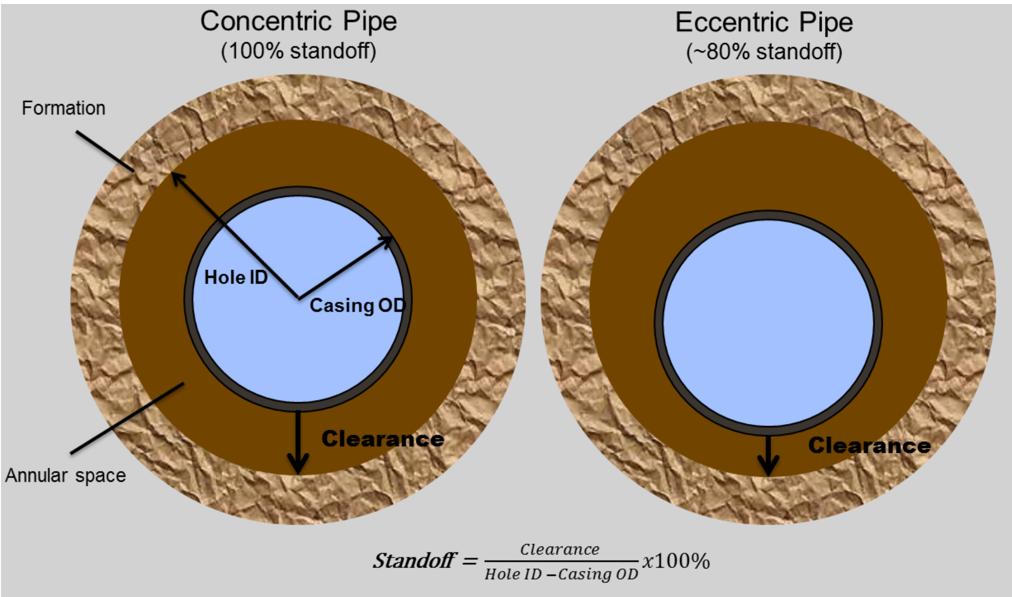

Figure 2: Calculated Standoff (modified after [16])

The openhole size-data are primarily subject to the drillbit size but should nevertheless be confronted together with lithology conditions to account for soft, unconsolidated zones which may

[1]MWD = Measurement While Drilling, LWD = Logging While Drilling

be unstable and thus affect the actual size of the hole. The theoretical size of the borehole is commonly referred to as gauged hole, while the actual hole size may differ from this due for instance washouts or collapse. Shape and size of the hole affects slurry volume, well control, and even displacement mechanics for the pumped cement. Different tools are available to to obtain sufficient holesize data including wireline caliper tools with arms, and ultrasonic tools. It is also possible to perform acoustic measurements, nuclear measurements, and resistivity measurements in conductive drilling fluids during the drilling operation (MWD and LWD tools). Various combinations and versions of the previously mentioned measurement techniques have been developed [11] to provide more accurate information on hole shape and trajectory which is favourable for centralizer placement and drilling-fluid removal, and thus also for the final cementing operation. The required casing properties are determined by the mechanical stresses and corrosive effects that the pipe is expected to experience during its expected lifetime. High differential pressures across the pipe wall can result in the burst or collapse of the casing, while dead weight and buoyancy effects can cause the casing to stretch and compress, respectively. Corrosion of the casing arise from formation fluids with corrosive effects that are unfortunate to certain metallurgies.

3.3.3 Wellbore Environment

The environment is determined by several factors and will change along the wellbore. Challenges to the cementing operation include the presence of pay zones, overpressured formations, low fracture gradients, and massive salt zones. Hence it is necessary to map the pressure regime along the entire openhole section which is usually based on formation pressure data obtained from logs. The data can, in the absence of logging equipment, also be extracted by looking at the mudweight which will give a fair indication of maximum pore pressure in any given interval [11]. A *kick* will for instance provide important formation about the pore pressure. When it comes to the risk of fracturing the formation, a mean fracture-pressure gradient is normally provided for each openhole section and is based on either leakoff testing or a formation integrity test. It is also possible to obtain information on formation pressure from: formation tests including fluid sampling and pressure readings; stimulation and squeeze cementing jobs performed in offset wells; LWD and annular pressure-while-drilling measurements [11]. Pay zones should be handled with care to avoid any slurry filtrate to leak into the reservoir, and especially if the interval to be cemented consists of fractured and/or depleted reservoir rock as one might risk losing the whole slurry deep into the formation [11]. Pay zones must also be adequately isolated from both each other and from non-productive zones, and zones containing gas or brine should be handled with care by possibly applying special cement slurries to prevent the fluids from migrating through the cement as it settles in the annulus.

The presence of drilling fluids in the annulus is unfavorable for the cementing job as most slurries are incompatible with drilling mud [11]. Therefore, in order to avoid these two fluids to commingle, it is common to pump a fluid in between that is compatible with both the drilling fluid and the cement. Applicable fluids for the separation are called *spacers* or *chemical flushes*, and the the usage of each depends on how heavy the fluid must be to maintain well balance (spacers usually consist of weight material like barite). The spacer weight should be higher than the drilling fluid in place but lower than the cement slurry to be pumped in order to achieve rheological hierarchy. Oil based mud requires an extra effort by the spacer fluid to ensure compatibility and to remove any oil film from the surface of the casing or the formation. This is achieved by adding solvents or surfactants to the spacer fluid (or chemical flush) which have been tailored to the oil based fluid in place (particularly its base oil). The essential part prior to the cementing job is to ensure that the borehole is free of drilling fluids and that debris and cuttings have been circulated out at a sufficient rate for a sufficient period so that the casing and formation surfaces are left water wet. Whenever 100% mud removal cannot be assured the cement slurry may be modified to better meet its objective despite any commingling with presence drilling fluid [11].

3.3.4 Temperature Regime

There are three temperatures of major importance when planning a cement job: 1) the Bottom Hole Circulating Temperature (BHCT), 2) the Bottom Hole Static Temperature (BHST), and 3) the differential temperature between top and bottom of the cement column [11].

The BHCT is the theoretical temperature the slurry will experience once it is placed in the well, and it is decisive for the selection of additives to the slurry such as *retarders*[1]. The BHCT can be calculated from temperature schedules from ISO/API standards, but these are based on assumptions that may not concur with the certain well conditions. Hence there are different methods for measuring temperatures during the drilling and circulating process (LWD or MWD) and computer simulators are used to derive the temperature regime based on several well parameters related to heat transfer including annular geometry (flow and contact area), fluid rheology, flow rate, and injection temperature [11]. The BHST is the undisturbed temperature at the bottom of the wellbore and is used to predict the compressive strength build-up rate and the long-term stability of a given cement system. The BHST is usually extracted from the geothermal gradient at the very location or estimated from log measurements. The differential temperature between top and bottom is important to avoid that cement slurries with retarders designed for a specific placement time at BHCT fails to settle when circulated to a shallower depth, i.e. it remains liquid or does not develop strength as intended. A useful guideline to avoid this unfortunate scenario is to ensure that the static temperature at the top of the cement exceeds the BHCT [11]. In cases where the latter criterion cannot be met, compressive strength tests under TOC (Top of Cement) conditions should be performed and if these tests yield inadequate results the cementing job should be executed in multiple stages.

3.3.5 Placement Techniques

Mud removal is the single most important requirement for the primary cement job to be successful [11]. Spacers and chemical flushes are used to separate mud from cement when the slurry is pumped down the pipe and displaced up the annulus, as discussed under *3.3.3Wellbore Environment*. Simulations are used to approach all wellbore and fluid parameters, ensure sufficient circulating time to remove the mud film in the annulus, and to make sure that two incompatible fluids do not commingle with each other during the operation. The composition of the spacer fluid depends not only on the mud type, but also on the required flow regime (laminar or turbulent), the formations involved, and the cement slurry design. Fluid dynamics will also affect the displacement efficiency, and models based on the desired rheological behaviour of the various fluids are available to achieve a good spacer composition [11]. Casing centralization is crucial to

[1]Additive to adjust thickening time

displacement efficiency as the fluids will flow more readily where the spacing between the casing and the formation is good (commonly known as the path of least resistance). Centralizers are used to straighten out the casing string but issues related to increased friction, casing rigidity, and borehole geometry, may reduce the number of centralizers that can be used. Hence it is necessary to achieve the highest possible standoff by optimizing the placement of each centralizer. Computer models are used to generate an overview of the standoff and position of the casing string in the wellbore, which then is used to optimize the location of each centralizer.

4.0 Cement Evaluation

4.1 The Cement Sheath

The cement sheath between the casing and formation has two primary functions: (1) to provide support for the casing and (2) to ensure that all zones of interest are hydraulically isolated from each other [16]. In order to validate if the cement sheath fulfills both objectives and that it coincide with prevailing standards one need to run logging tools in the well and analyze the cement sheath. The NORSOK D-010 states that the function of the casing cement as a Well Barrier Element (WBE) is to "provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally [17]. Further, the standard states that verification requirements for having obtained the minimum cement height shall be described by either logs (CBL, temperature, LWD sonic), or by estimation on the basis of records from the cement operation (volumes pumped, returns during cementing, etc.) [17].

The information retrieved from cement-evaluation logs will often constitute the basis for important and costly decisions with respect to remedial cementing operations. Misinterpretation of a log or misapplication of a tool can both provide erroneous data that might lead to a non-isolated section being overlooked, or unnecessary initiation of well treatments.

4.2 NORSOK

The NORSOK standards are developed by the Norwegian petroleum industry to provide the necessary instructions for the safe and cost efficient execution of petroleum related operations on the NCS. The NORSOK standards are normally based on recognized international standards with additional provisions to meet the requirements of the Norwegian petroleum industry. The intentions for the NORSOK standards are, as far as possible, to replace individual oil company specifications, and to serve as a reference source within authority regulations. The NORSOK D-010 [17] standard defines minimal requirements and guidelines for well design, planning and execution of well operations in Norway, including the cementing process. Only requirements relevant to cementing and cement evaluation operations are addressed in this section, but the NORSOK D-010 [17] can be approached for more detailed reading. Note that this thesis has approached the NORSOK D-010 rev 3 published in 2004 as it was the prevailing regulation during most of the cases studied. NORSOK D-010 rev 4 was however published June 2013 and constitutes the current standard.

4.2.1 NORSOK D-010 Well Integrity in Drilling and Well Operations

(Rev 3, august 2004)

A well barrier is described by NORSOK D-010 [17] as an envelope of one or several dependent barrier elements that prevents unintentional flow of fluids or gases from the formation, into another formation or to surface. (Primary well barrier is the first objective that prevents flow from a source like e.g. strippers and CT BOP, while a secondary well barrier is the second objective that prevents flow from a source like e.g. lower riser package and wellhead.) A well barrier element (WBE) is described as an element that alone is unable to prevent a flow from one side to the other side of itself. Table 22 on page 132 in NORSOK D-010 [17] lists the requirements for casing cement as a well barrier element in the well. The requirements refer to solid state cement located in the annulus between the casing/liner and the formation, or between concentric casing strings. The purpose of casing cement as a barrier element is to provide a continuous, permanent and impermeable hydraulic seal to prevent flow of formation fluids, resist pressures from above or below conditions, and to structurally support casing or casing strings. Cement used to form a plug in the wellbore under plug and abandonment (P&A) operations will for the record have some different acceptance criteria than for the casing cement. The criteria for a cement plug will however not be addressed in this paper but can be approached using Table 24 in NORSOK D-010 [17]

The NORSOK D-010 [17] lists seven acceptance criteria related to the design, construction and selection of the casing cement. The acceptance criteria include:

1. A design and installation specification (cementing program) shall be issued for each primary casing cement job.
2. The properties of the set cement should be capable to provide lasting zonal isolation and structural support.
3. Cement slurries used for isolating permeable and abnormally pressured hydrocarbon bearing zones should be designed to prevent gas migration.
4. The cement placement technique applied should ensure a job that meets requirements whilst at the same time imposing minimum overbalance on weak formations. Equivalent Circulating Density (ECD) and the risk of lost returns during cementing shall be assessed and mitigated.
5. Cement height in casing annulus along hole (TOC):
   - 5.1. General: Shall be 100 m above a casing shoe, where the cement column in consecutive operations is pressure tested/the casing shoe is drilled out.
   - 5.2. Conductor: No requirements as this is not defined as WBE.
   - 5.3. Surface casing: Shall be defined based on load conditions from wellhead equipment and operations. TOC should be inside the conductor shoe, or to surface/seabed if no conductor is installed.
   - 5.4. Casing through hydrocarbon bearing formations: Shall be defined based on requirements for zonal isolation.Cement should cover potential cross-flow interval between different reservoir zones. For cemented casing strings which are not drilled out, the height above a point shall be 200 m, or to previous casing shoe, whichever is less.
6. Temperature exposure, cyclic or development over time, shall not lead to reduction in strength or isolation capability.

7. Requirements to achieve the along hole pressure integrity in slant wells to be identified.

In addition to the above requirements the NORSOK D-010 [17] standard lists certain acceptance criteria regarding the initial verification of the casing cement, i.e. whether the job can be determined as a success or not. There are three acceptance criteria for the initial verification, including:

1. The cement shall be verified through formation strength test when the casing shoe is drilled out. Alternatively the verification may be through exposing the cement column for differential pressure from fluid column above cement in annulus. In the latter case the pressure integrity acceptance criteria and verification requirements shall be defined.
2. The verification requirements for having obtained minimum cement height shall be described, which can be:
   2.1. Verification by logs (cement bond, temperature, LWD sonic), or
   2.2. estimation on the basis of record from the cement operation (volumes pumped, returns during cementing, etc.)
3. The strength development of the cement slurry shall be verified through observation of representative surface samples from the mixing cured under a representative temperature pressure. For HPHT wells such equipment should be used on the rig site.

4.3 Cement Bond Logging (CBL) Tools

4.3.1 Operating Principles

The two objectives of the cement are commonly referred to as providing a shear and hydraulic bond between the casing, cement and formation; a shear bond supports the casing while a hydraulic bond blocks the flow of fluids. A conventional CBL tool consists of one transmitter and two receivers which are usually located three feet and five feet from the transmitter. The CBL tool is run in the cased hole, and the transmitter emits and omnidirectional acoustic energy pulse that propagates through the borehole fluid as an expanding circular wave encompassing the entire borehole until it strikes the casing ID. When the acoustic wave strikes the casing ID it will be refracted according to Snell's law:

$$\frac{V_1}{sin\alpha_1} = \frac{V_2}{sin\alpha_2}, \tag{1}$$

where:
$\alpha =$ the angle of incidence and refraction
$V =$ the velocity of sound in the respective materials

At a specific angle of incidence, typically referred to as the *critical* angle, the acoustic wave will refract directly down the casing as a pressure pulse (compressional wave). Because the path parallel to the casing is the shortest from the transmitter to the receiver, the casing wave is usually the first to arrive at the receiver. The CBL tool contains certain features that are unfavorable for acoustic wave propagation to ensure that the first signal recorded at the 3-foot receiver is the casing wave and not a wave travelling through the tool itself. For incident angles smaller than the critical angle the acoustic wave will be refracted out through the casing and then back to the receiver via a path that will depend on the quality of the acoustic coupling of the cement to the casing and the formation. A common bond log today is comprised of three separate measurements: casing signal amplitude, transit time (TT), and the total acoustic waveform.

4.3.2 Casing Signal Amplitude

Casing signal amplitude is a function of the amount of energy arriving at the receiver (usually recorded at the 3-foot receiver) and provides the basis for cement bond evaluation. The principal of the amplitude measurement for cement evaluation is based on the common assumptions that [16]:

1. Maximum amplitude indicates that the casing is free to vibrate and hence absent from cement effects, i.e. “Free Pipe”.
2. Minimum amplitude indicates the pipe is unable to vibrate and thus must have cement completely surrounding the pipe, i.e. “Bonded Pipe”.
3. Readings between maximum and minimum amplitude indicate a “partial bond condition”.

The basis for these previous assumptions is that the presence of cement against the pipe will reduce the casing signal in a similar way as the ring of a bell will be reduced if you hold it tightly in your hand. The amplitude of the acoustic signal will hence indicate the degree in which cement is presence, i.e. free pipe will yield low attenuated signals with high amplitude, while a fully bonded cement job will yield highly attenuated signals with low amplitude [16].

The amplitude of a wave will gradually decrease as it propagates through a medium. This phenomenon is referred to as *attenuation*, and by measuring the amplitude of the wave at two reference points with known separation, the level of attenuation can be expressed by the following mathematical relationship:

$$a = \frac{20}{z} log_{10} \frac{A_1}{A_2} [dB], \tag{2}$$

where:
a = attenuation factor
z = distance between transmitter and receiver
A_1 = Amplitude at transmitter
A_2 = Amplitude at receiver

For the common acoustic logging tool (CBL) consisting of a transmitter and two receivers (3-foot and 5-foot receivers), attenuation information is usually obtained by recording the amplitude of the acoustic signal at one of the receivers (usually at the 3-foot receiver). The calculated attenuation factor is then derived from the amplitude ratio between the initial wave at the transmitter and the recorded amplitude at the receiver. The actual attenuation of the acoustic signal is a composite function of various terms that will be described in some detail shortly. The involved terms will help understand the behaviour of acoustic waves and thus how sonic tools are able to yield data on cement quality. Assuming a constant transmitter output the attenuation of an acoustic signal downhole can be described as follows:

$$Attenuation = f(M, E, G, H), \tag{3}$$

where:
M = attenuation over each borehole fluid element due to acoustic losses in the fluid
E = attenuation due to partial transmission at the fluid/casing interface
G = attenuation over the casing segment due to frictional losses in the steel
H = attenuation due to energy transfer by radiation from the casing to the adjacent media

The acoustic attenuation caused by the wellbore fluid (M) depend on the viscous damping of the fluid and can differ considerably between different types of completion fluids. The difference has traditionally been considered negligible in cased hole logging [18] and nomographs and charts have been developed assuming fresh water as wellbore fluid. However, the nomographs used for determining cement strength from CBL amplitude measurements are prone to provide erroneous results if completion fluids like $CaCl_2$, $ZnBr_2$ and $CaBr_2$ are used instead of water. Charts have been developed to compensate for the differing damping effects between water and completion fluids, and Figure 3 presents such a chart for borehole fluids with various densities. The Y-axis of the chart shows the ratio between measured E1 amplitude in the given wellbore fluid and the measured E1 amplitude in fresh water. The lower X-axis show the weight of the borehole fluid in pounds per gallon (lb/gl) while the upper x-axis shows the same weight in specific gravity (SG). The drawn example-lines illustrate how the amplitude in fresh water would be increased by a factor of 1.60 if a 12.5 lb/gal (1.5 SG) completion fluid is used instead of fresh water [18].

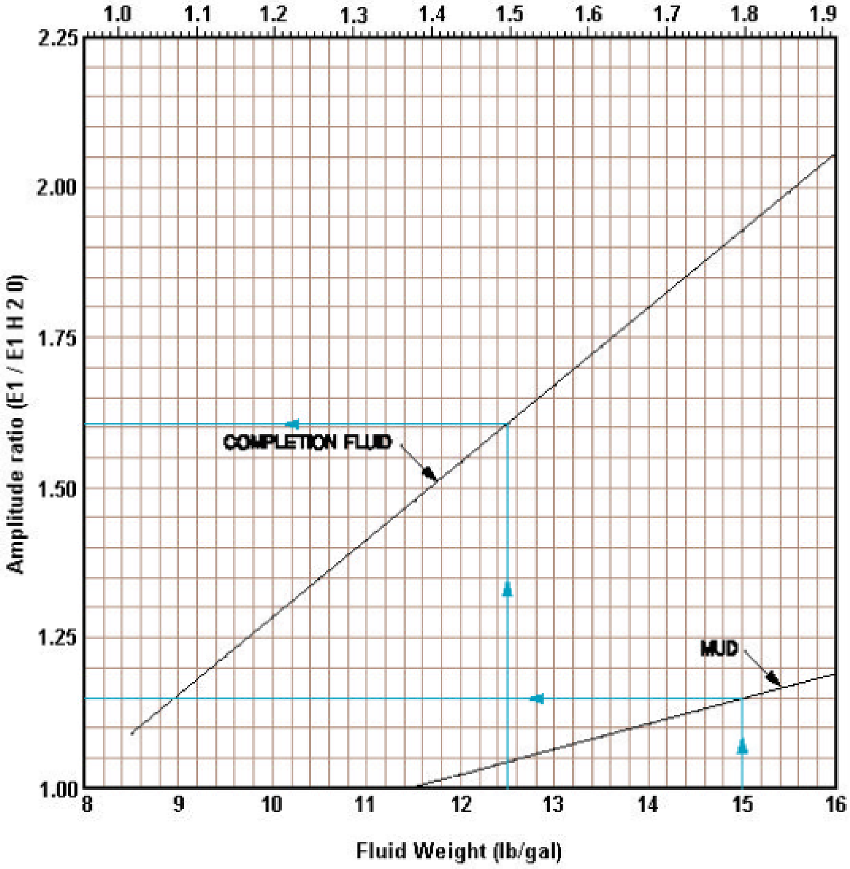

Figure 3: Damping Effect of Drilling Fluids [18]

Attenuation at the interface of the borehole fluid and the casing wall is caused by partial transmission and mode conversion when the acoustic wave is refracted into the casing. The attenuation effect depends primarily on the contrast in acoustic impedance between the borehole fluid and the casing steel. Acoustic impedance is given by the following equation:

$$Z = \rho V, \tag{4}$$

where:
ρ = density
V = velocity

However, experimental data (Guyod, 1969, cited in [18]) has shown that the presence of cement in the annulus has little or no impact on acoustic losses in the borehole fluid and hence it play a minor role for cement bond evaluation.

Attenuation effects caused by frictional losses when the acoustic signal travels down the casing is another term that can be considered negligible as it only constitutes a very little fraction compared to the effects caused by radiation. Radiation occurs as the wave travels down the casing and it is the only attenuation term that actually depend on the conditions in the annulus, i.e. to what extent cement is presence. A good cement bond, usually described as a cement sheath greater than 3/4 inches encapsulating the casing [18], will prevent the pipe to vibrate and hence attenuate the amplitude of the acoustic wave. Different velocities in steel and cement cause a continuous disturbance for the wave at the steel-cement interface and some of the energy from the initial wave will be transferred into the cement. The radiation continues as the wave travels down the casing resulting in the gradual decrease in amplitude commonly referred to as attenuation. Theoretical and experimental studies on a steel plate with well bonded cement on the one side were carried out by G.H. Pardue and associates [18]. Based on these studies the attenuation rate was found to follow the equation given by:

$$Attenuation[dB/ft] = \frac{52.2(\frac{\rho_{cement}}{\rho_{steel}})(\frac{1}{t})}{\left[(\frac{v_{plate}}{v_p})^2 - 1\right]^{-\frac{1}{2}} + \left[(\frac{v_{plate}}{v_s})^2 - 1\right]^{\frac{1}{2}}}, \quad (5)$$

where:
ρ_{cement} = density of cement
ρ_{steel} = density of steel plate
t = thickness of plate in inches
v_p = the compressional wave velocity in cement
v_s = the shear wave velocity in the cement

The attenuation calculated by Equation 5 depends on both the compressional wave velocity and the shear wave velocity of the cement, but the latter will usually be the dominating factor as revealed by the equation. The change in attenuation ratio as the cement cures is hence primarily as result of increased stiffness in the cement. Experiments have confirmed that the compressive strength of the cement, i.e. the pressure that causes fracturing or crunching, is a function of the shear modulus of the cement. Since the shear wave velocity of the cement (v_s in Equation 5) is a function of the cement shear modulus [18], the attenuation rate should consequently be a function of the compressive strength of the cement. Further experiments confirmed this connection and the data obtained were used to create a nomograph that gives the relation between the compressive strength of well bonded cement and the casing signal amplitude. Halliburton has through research constructed a similar nomograph for the CBL tool and this is shown in Figure 4.

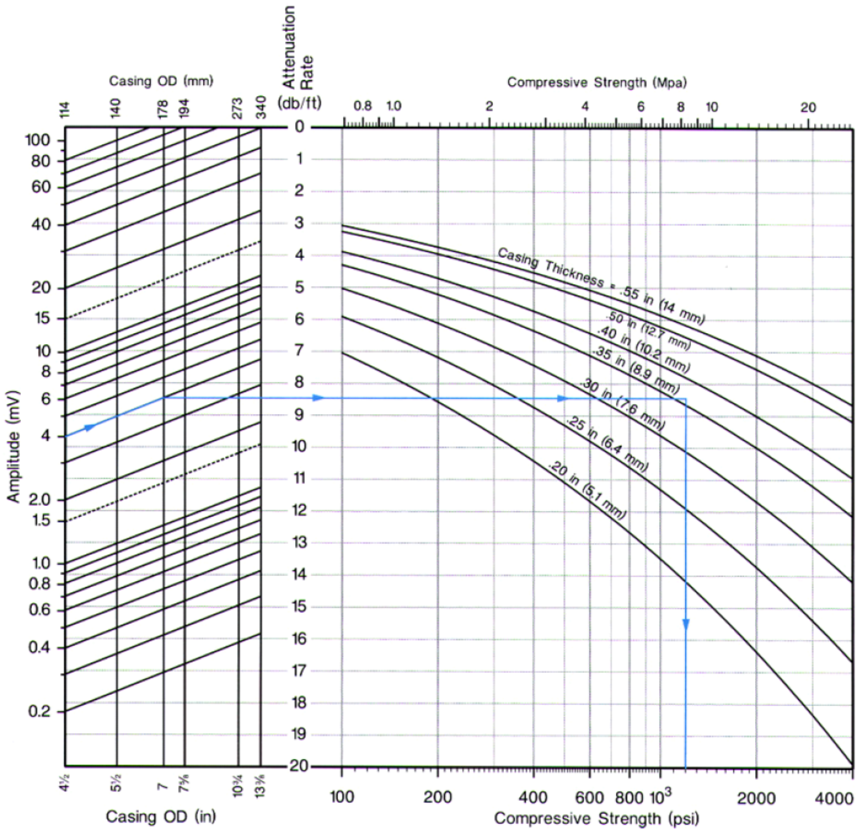

Figure 4: Cement Bond Log Interpretation Chart [18]

Equation 5 further states two important features with respect to cement bond evaluation. The first is that in order for the cement to fully attenuate the signal there must be shear coupling at the casing-cement interface. So, for pipe segments where there is a small fluid annulus between the casing and the cement, commonly referred to as a microannulus, the signal will undergo partial attenuation depending on the thickness of the gap. Hence, the amplitude for an interval with a microannulus present will be greater than for a good bond, but less than for free pipe. The second feature is that the attenuation is inversely proportional to the casing thickness and directly proportional to the cement density. A thicker casing will hence give less attenuation and the pipe signal will become higher even though a significant cement sheath is in place. Table 1 shows how the pipe amplitude ranges from 0.7mv to 3.5mv as the thickness of a 5-1/2 inch OD casing increases (illustrated by an increase in total weight, WT), and chart X in appendix X is used for converting casing weight and casing OD to a thickness value. Whenever a non-standard weight of pipe is used it is common to suspect a thick pipe amplitude effect, i.e. a worst case scenario with respect to pipe thickness is adopted to avoid any overconfidence in the cement sheath.

Table 1: Amplitude and Casing Weight (Thickness) [18]

Casing Size	WT.	Travel Time u-SEC	Free Pipe Signal	3000 PSI 100% Cement	60 % Bond Cut Off	Interval for Isolation
5-1/2"	15.5 17.0 20.0 23.0	269	72mv	0.7mv 1.0mv 2.1mv 3.5mv	4.8mv 6.0mv 9.0mv 13.0mv	6 ft

Equation 5 was derived assuming there is an infinitely thick section of cement bonded to the one side of the casing. Obviously, this is not the real case, though experiments revealed that cement sheaths thicker than ¾ inches can be considered *infinite* and that full signal attenuation can be expected as long as the cement sheath reaches a thickness of ¾ inches or more. Full signal attenuation will hence not be obtained if the cement sheath is less than ¾ inches even though the cement bond to pipe is good. Figure 5 shows the attenuation rate as a function of cement sheath thickness and the given relation enables amplitude corrections whenever a thin cement sheath is suspected. The graph clearly illustrates how thin cement sheaths have a much lower attenuation capacity (radiation transfer factor) than those with a thickness greater than ¾ inches. To determine whether a thin cement sheath is present or not one can use the open-hole caliper log or the bit size of the drilled section to get the borehole diameter. If the casing OD subtracted from the borehole diameter or the bit size is less than 1.5 inches, a thin cement sheath is present. Note that when subtracting the casing OD from the wellbore ID the difference must be divided by two to get the annular thickness around the casing.

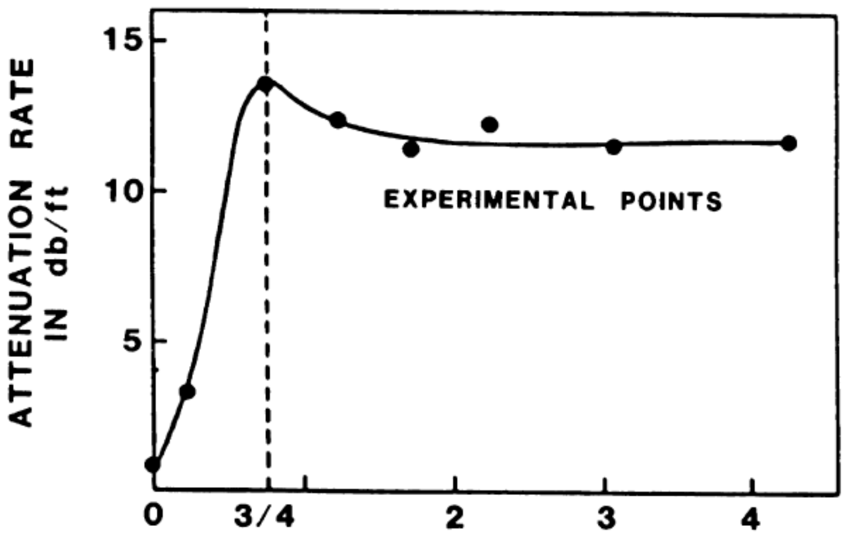

Figure 5: Thin Cement Sheath [18]

4.3.3 Transit Time (TT)

Transit Time (TT) is the time it takes for the acoustic signal to travel from the transmitter through the borehole fluid, down the casing, back through the fluid, and finally be picked up by the 3-foot receiver. The measured transit time curve has two primary objectives: 1) to qualify that the tool is centralized in the borehole, and 2) to help confirm fast formation arrivals. For the area above TOC, i.e. *free pipe* condition, the transit time curve should be a straight line with only a short increase at each casing collar which are caused by fluid gaps that slightly attenuates the pipe wave amplitude and thus increases the transit time (Fitzgerald, 1983, cited in [18]). For the area below TOC the transit time curve becomes more fluctuating due to influencing factors that either increase or reduce signal transit time with respect to the free pipe section. The various factors that affect the TT are as follows:

Longer Transit Time (*Signal Stretch* and *Cycle Skipping*)

Signal stretch can occur when the first pipe arrival is detected in a bonded interval so that the signal amplitude is slightly attenuated. When the amplitude of the received signal decreases the transit time will increase, as illustrated in Figure 6. *Cycle skipping* can occur if the pipe arrivals have been attenuated by the presence of cement. The attenuation causes the signal to become so flattened that its first arrival or even arrivals are not detected at the receiver. Cycles can therefore be skipped and if the pipe is well bonded one can even miss the entire pipe signal and jump to formation arrivals.

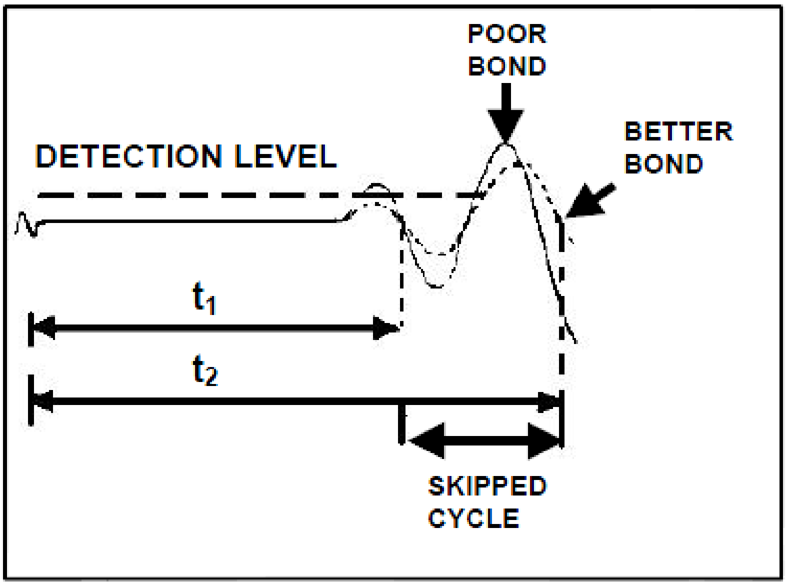

Figure 6: Signal Stretch and Signal Cycle Skipping [16]

Shorter Transit Time (Tool Eccentricity and Fast Formations)

If a tool is not properly centralized in the borehole the transit time will become shorter, as illustrated in Figure 7. How much shorter the transit time will be depends on the degree of eccentricity. Tool eccentricity will affect the amplitude as well, and the more off-centered the tool is the lower the recorded amplitude will be. In order to identify tool eccentricity the sensitivity for the time scale should be at least 100 microseconds per log track [16]. *Fast formation* arrivals can occur if consolidated formations with transit time greater than steel are present around the bore. The sound will travel faster through the formation then down the casing steel and thus arrive at the receiver ahead of (or at the same time as) the casing signal. These early arrivals contaminate the amplitude curve with respect to quantitative interpretation of cement bonding because it will be subject to both formation and casing properties. However, the case is not problematic as it has been documented that fast formation arrivals can only occur ahead of (or simultaneously with) casing arrivals if there is a good acoustic coupling between casing, cement, and the formation[16], which means that the overall bond is rather good. The total energy display (discussed below) can be used to determine whether fast formation arrivals are present or not and thus also to decide whether short transit times are caused by fast formations or tool eccentricity.

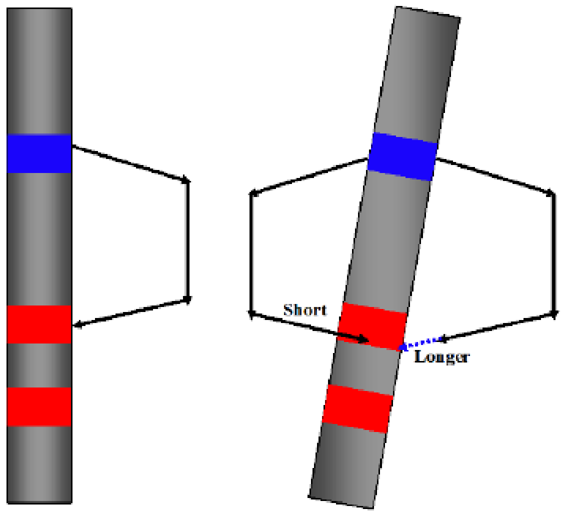

Figure 7: Tool Eccentricity [16]

4.3.4 Total Acoustic Waveform

The total energy of the signal is recorded at the 5-foot receiver in order to obtain better spacing between waves so that they become easier to separate and identify. The time scale is usually in the range of 200 to 1200 microseconds and there are two primary ways to present acoustic waveforms. The first is by an XY-plot which provides an unprocessed presentation of the signal with time along the X-axis and amplitude along the Y-axis. The second is by Microseismogram (MSG) or Variable Density Log (VDL) which are processed presentations of the acoustic signal recorded on a continuous log. The conversion from a full wavetrain display in the XY-plot to a linear representation in the MSG or VDL is illustrated in Figure 8. Due to the waveform size the XY-plot cannot obtain more than one sample per foot, while the linear representation permits more samples per linear foot which better defines the casing-cement coupling [16]. The total energy display is the most important part of the CBL as the MSG/VDL provides information on both cement to casing bond and cement to formation bond, where the latter will allow for qualitative interpretations of the cement to formation bond. For comparison, the pipe amplitude only provides information about cement to casing bond, while the transit time is only used to investigate fast formations and tool eccentricity effects.

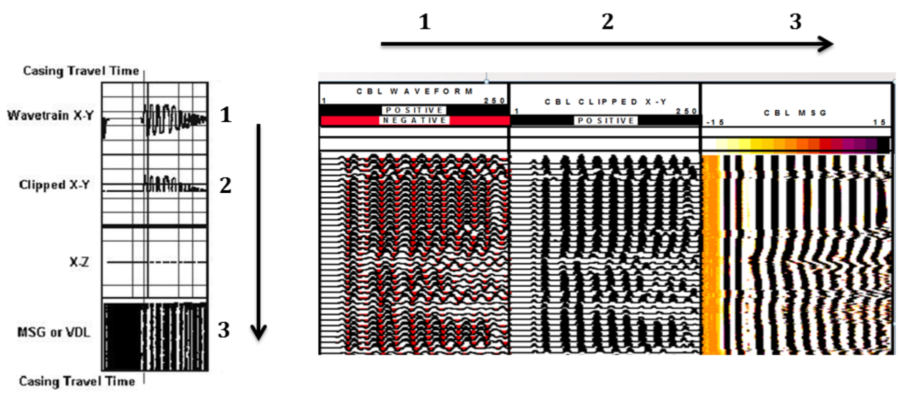

Figure 8: VDL/MSG Processing(modified after [16])

4.4 Ultrasonic Evaluation Tools

In addition to the CBL tools it is common to run ultrasonic cement evaluation tools to aid the overall cement sheath evaluation. Ultrasonic tools offer improved information on the cement to pipe bond, but because the tool is only able to detect the material most immediate to the casing it provides no information on the cement to formation bond. Ultrasonic tools should therefore be run in conjunction with the conventional CBL to achieve better evaluation of the cement sheath, and it is especially advantageous (and almost required) for evaluating complex cement blends like foam, latex, ultra-low strength, or even cement contaminated by gas [16]. Ultrasonic tools are also able to obtain casing information (thickness and ID) simultaneously as cement information is being recorded. The ultrasonic tools are as mentioned combinable with the CBL tool and all data for both cement and casing evaluation can be recorded in one single run.

There are two generation of ultrasonic tools developed for the industry and both generations utilize transducers instead of the separate transmitter-receiver setup that characterizes the CBL tool. The first generation 8-transducer tool from Schlumberger is the C.E.T while the 8-transducer tool from Halliburton is called the P.E.T. The second generation ultrasonic tools utilize one single rotating transducer (instead of multiple fixed ones) that provides high-resolution circumferential data. Schlumberger has developed the USIT while Halliburton provides the CAST-V tool. The CAST-V has been modified into newer models (CAST-F, CAST-M) but the basic principle remains. These second generation ultrasonic tools will provide 36 to 200 measurements per depth sample, at a vertical sample rate ranging from 2 to 12 samples per foot, depending upon the service company [16].

4.4.1 Operating Principles

The ultrasonic tool utilizes contrasts in acoustic impedance between the material in contact with either the inner or outer surface of the casing and the casing itself. The contrast is presented by the ultra-sonic signal reflection coefficient, C_r, given by the following equation:

$$C_r = \frac{Z_1 - Z_2}{Z_1 + Z_2}, \tag{6}$$

where:
Z_1 = acoustic impedance of the casing equal to $10^6 kg/m^2 sec$
Z_2 = acoustic impedance of the material in contact with the casing surface (inside or outside)

The acoustic impedance, Z, is given by:

$$Z = \rho_b V_c, \tag{7}$$

where:
ρ_b = bulk density
V_c = the composite velocity of a sonic signal

The amount of energy reflected and transmitted at each reflecting surface is easily calculated by means of the ultrasonic reflection coefficient, C_r (6), where the computed value yields how much of the signal is being reflected at that particular interface, i.e. a C_r value equal to 0.95 implies that 95% of the signal is reflected while 5% of the initial signal is refracted through. Acoustic impedance values for materials commonly involved in the downhole logging environment are presented in Table 2 below.

Table 2: Typical Acoustic Impedance Values [18]

Material	Velocity (km/s)	Density (gm/cm^3)	Impedance (MRayls)
Fresh water	1.52	1.00	1.52
Salt water (200 kppm)	1.74	1.14	1.98
Diesel oil	1.25	0.80	1.00
Free gas	0.38	0.001	0.10
Water-base mud (8 lbm/gal)	1.44	0.96	1.38
Water-base mud (16 lbm/gal)	1.40	1.92	2.69
Oil-based mud (8 lbm/gal)	1.34	0.96	1.29
Oil-based mud (16 lbm/gal)	1.20	1.92	2.30
Class H cement (12 lbm/gal)	3.1	1.55	4.8
Class H cement (16.6 lbm/gal)	3.2	1.94	6.21
Lightweight cement (12 lbm/gal)	3.10	1.80	4.81
Steel	5.90	3.23	45.43

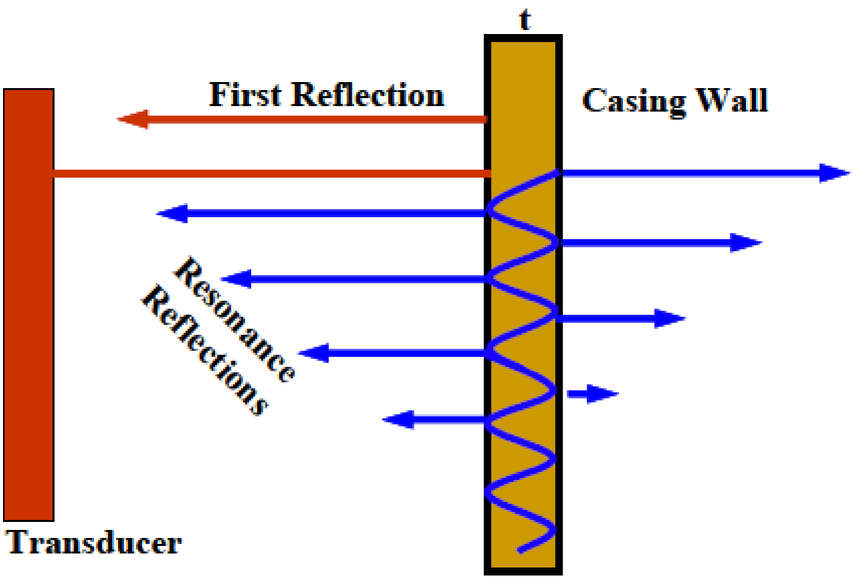

Figure 9: Ultrasonic Signal Path [16]

When sound is transmitted from the transducer the wave travels through the medium around the tool until it strikes the casing ID, as illustrated in Figure 9. Once the signal strikes the interface between the medium around the tool, say mud, and the casing steel, a portion of the signal will be reflected back to the transducer while the rest will be refracted through the casing until it strikes the next interface between the casing OD and the annulus material. A portion of this signal will be reflected while the rest is refracted into the medium on the outside of the casing, like for instance cement. The portion reflected at the casing-cement interface will be reflected again at the casing-mud interface and for each reflection there will also be refraction of the signal that transmits a pulse into the immediate material which will usually be cement and mud, respectively. This series of reflection/refraction will continue as the signal is gradually attenuated. However, it is only the initial reflection value (at mud-casing ID interface) and the early part of the signal (from immediately beyond the casing OD) that are processed in order to eliminate later reflections from the outer casing (if concentric strings), the bore hole, or the formation [16]. When the reflected signal reaches the transducer it is converted to a waveform which is used to determine casing ID, casing thickness, and the acoustic impedance of materials in place at each reflective surface, as illustrated in Figure 10 below.

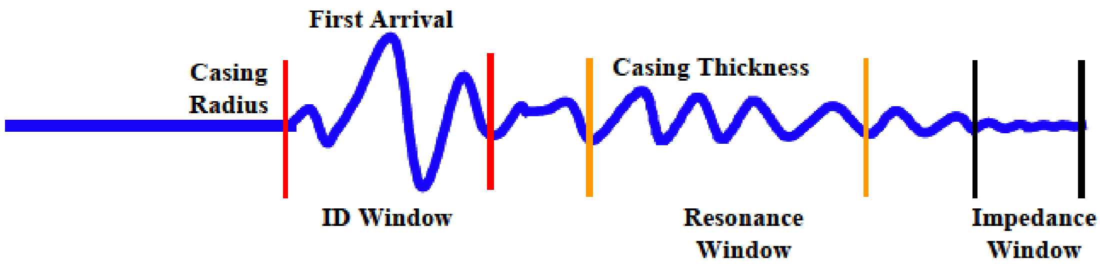

Figure 10: Ultrasonic Waveform Breakdown [16]

The “ID Window” in Figure 10 gives the reflected energy level and time interval to the casing ID and is used to determine the casing ID. The waveform amplitude also gives an indication of the casing conditions. For the casing thickness calculations the tools use different frequencies for the rotating transducers in order to optimize the final calculations (250 kHz, 350 kHz, and 450 kHz for the CAST-V, and a range from 195 to 650 kHz for the USIT [18]). The selection of frequency depends upon the casing thickness as the objective is to make the pipe resonate in its first harmonic mode (resonance) [18]. For the right frequency mode the casing thickness can be calculated by applying *standing wave theory* which states that: when the pipe is resonating at its first harmonic, f_0, mode, the distance between the front and back of the pipe (thickness) will be equal to half the wavelength ($\frac{\lambda_0}{2}$). The “Resonance Window” in Figure 10 is hence used to determine the casing thickness together with the following equations:

$$c = f_0 \lambda_0 \qquad \lambda_0 = \frac{c}{f_0} \qquad t = \frac{c}{2f_0}$$

where:
c = velocity through steel
f_0 = casing resonance frequency
λ_0 = wavelength
t = casing thickness

The “Impedance Window” in Figure 10 is the primary measurement for determining the acoustic impedance of the material in the annulus [16]. The calculation of acoustic impedance requires ongoing corrections for second-order mud, pipe curvature, and casing wall thickness; and for ultrasonic tools using a scanning transducer (USIT and CAST) the acoustic impedance, Z_r, can be calculated by the following equation:

$$Z_c = a_0 + b_0 \times C_t + c_o \times log(Sum) + d_0 \times C_t \times log(Sum) \tag{8}$$

where:
Z_c = acoustic impedance of the material behind the casing
C_t = casing thickness
Sum = sum of amplitude maxima of the half-cycles in the waveform resonance window
a_0, b_0, c_0, and d_o are coefficients calculated from the theoretical simulations of known impedance and casing thickness (calculated for every scan)

4.5 Fluid Compensated Bond Tools

Because of the omnidirectional measurement technique of conventional cement bond logs they will experience limitations when it comes to issues like channeling. The Segmented Bond Tool (SBT) from Baker Hughes was developed not only to obtain such radial measurements of the cement sheath but also to provide a tool that was less affected by the type of fluid in the borehole. The type of tool is referred to as fluid-compensated bond tool [16], and the SBT consists of six or eight pads in direct contact with the inside of the casing, where each pad measures the average attenuation rate of the acoustic signal over its corresponding arc around the casing periphery. Charts that show the relation between casing thickness, amplitude readings (attenuation), and the compressive strength of the cement are used to calibrate the SBT prior to the logging operation (similar charts as the one in Figure 4 on page 18). The number of pads depends on the casing size, and the corresponding arcs will thus be either 60°(6 pads) or 45°(8 pads). The pads are organized so that the acoustic signal transmitted at one pad will travel through the casing and become the first arrival received at an adjacent pad, as illustrated by Figure 11. The distance between transmitter and receiver of the acoustic signal is only one foot, and the average attenuation rate of the acoustic signal is measured in decibel per feet (dB/ft). The principle behind the SBT measurement is the same as for the CBL such that a high attenuation rate from the SBT tool is equivalent to low recorded amplitude from the CBL. The SBT is usually ran with a separate sub to collect the VDL which is similar to the waveform data recorded at the 5-foot receiver for the CBL tool.

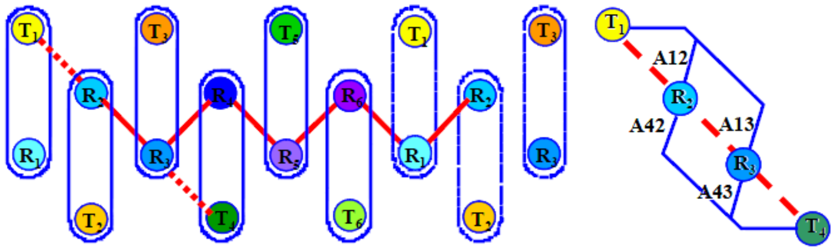

Figure 11: SBT Tool Configuration (6 pads)([16])

The SBT will present six (or eight) curves with the average attenuation rate from each pad as shown in Figure 12. Shaded curves represent an average attenuation rate that is greater than what is expected from a free pipe condition, i.e. shading indicates bonded pipe. The SBT log thus presents the ‘opposite’ data curves compared to the CBL, i.e. the SBT yields signal attenuation curves while the CBL gives the amplitude reading curves. Normally an attenuation rate greater than 10 dB/ft indicates excellent cement to casing bond [16], but the shape of the curves and how they change can be used for qualitatively evaluations as well including the separation between cement and fluid behind the casing. The homogeneity of a fluid will cause it to yield straight lines for the attenuation rate, while the heterogeneous (crystalline) structure of cement will produce more fluctuating attenuation rates, regardless of its compressive strength.

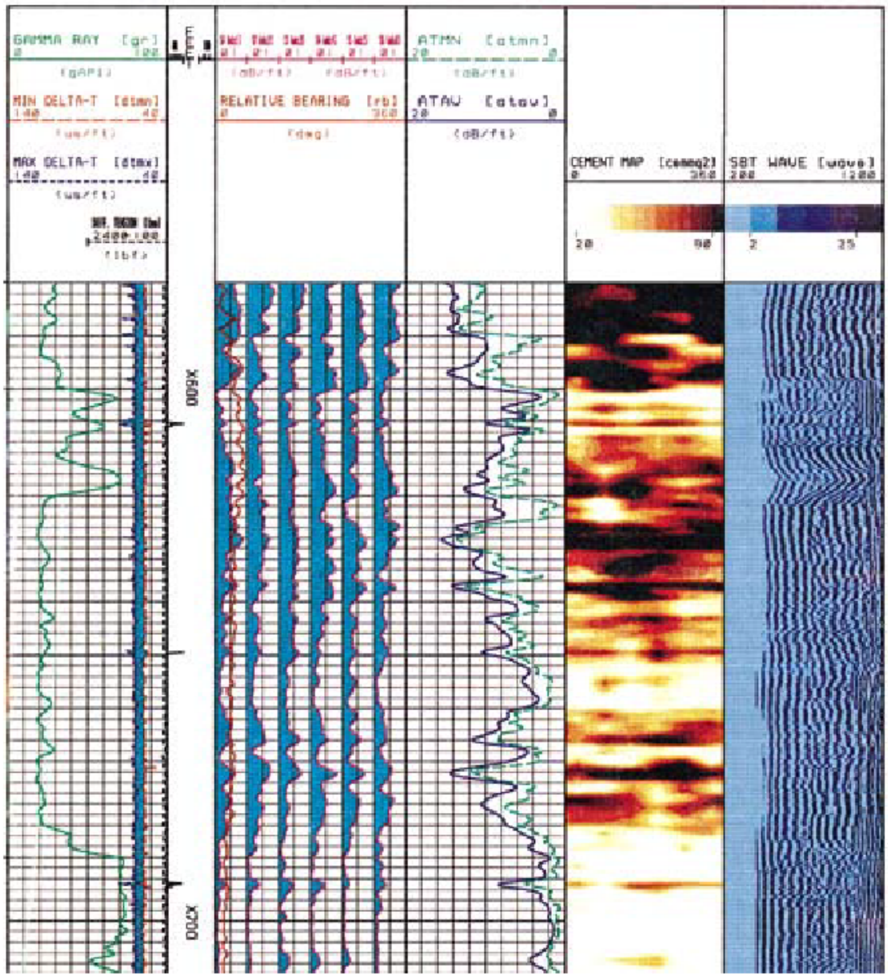

Figure 12: SBT log presentation([16])

4.6 ACE - Advanced Cement Evaluation

ACE is a newer processing method to better utilize the data obtained from conventional CBL and ultrasonic tools and it is valid and effective in both time and cost because it does not require additional logging passes [16]. It is a very helpful method to better evaluate the cement sheath, especially for foam and other complex cement types where conventional data can easily be misinterpreted which in turn can lead to unnecessary and costly remedial jobs. The problem with foam and other complex cement types is their wide range in acoustic impedance values which can be lower than water, drilling mud, or spacer fluid – and it can even approach the value of free gas, as shown in Figure 13. ACE calculates the level of activity for both CBL data and ultrasonic data and then generates a variance image that identifies small changes. The CBL variance will allow differences between free pipe, partially bonded pipe, and bonded pipe conditions to be more easily recognized, while the ultrasonic variance will allow detection of minor changes in cement or fluid compositions [16].

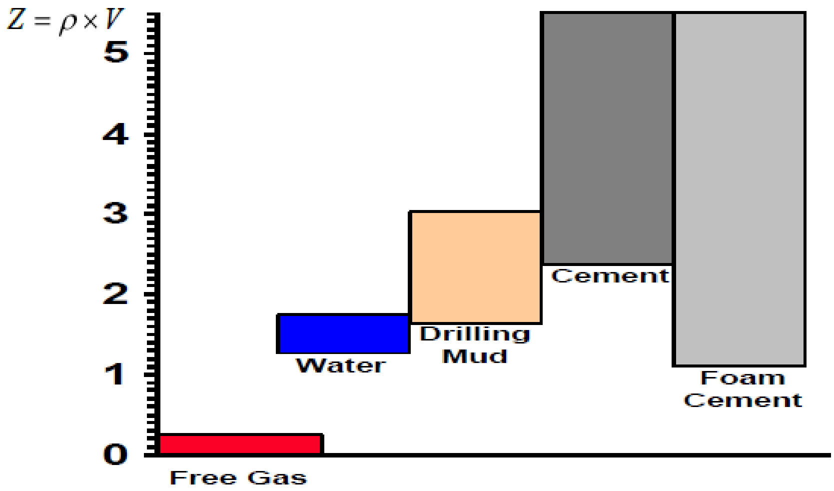

Figure 13: Acoustic Impedance values for Foam Cement [19]

4.6.1 ACE for CBL

Statistical Variance Processing (SVP) was developed to better reveal subtle variations in acoustic impedance so that solid and liquid phases with nearby impedance values could be distinguished, like in the case for foam cement and fluids. Further description of the SVP is described by Harness et al. (1992) and Frisch et al. (1998) (cited in [16]) and will not be elaborated here. The important part however is how the SVP technique in conjunction with CBL waveform data allows for the better visualization of differences in vertical waveform samples. The SVP coloring scheme displays small to large changes with light to dark colors, respectively, i.e. small changes are indicated by lighter colors while large changes are made dark. So for a free pipe section where differences in vertical samples are at minimal and the CBL displays distinguishable "railroad tracks" (i.e. small changes in acoustic waveform), the SVP coloring scheme will apply light color. For more bonded sections where the acoustic waveform is subject to more change the SVP coloring scheme will apply dark coloring. This is especially noticeable for collars as they will appear as dark wedges expanding from left to right in the *CBL Variance* track for the free pipe section, but as the cement to pipe bond increases the response from the collars is gradually reduced, as clearly illustrated in Figure 14 (Track number 2 from the right). When the *CBL MSG* is combined with *CBL Variance* the *CBL Total*is achieved (last track in Figure 14). The *CBL Total* displays the high amplitude portion of the CBL together with the vertical differences and thus provides a composite and useful presentation to assess the pipe to cement bond. It is also worth mentioning that ACE has helped cement sheath evaluation for overlapping casing intervals, which is evaluation of cement placed in the annular space between two concentric strings of pipe, like a liner lap. The difficulties when evaluating cement bond in the casing-casing annuli are due to excessive noise reflected from the outer string, i.e. the CBL will exhibit waveforms and amplitude values that will indicate poor bonding conditions. This will, however, not be discussed any further.

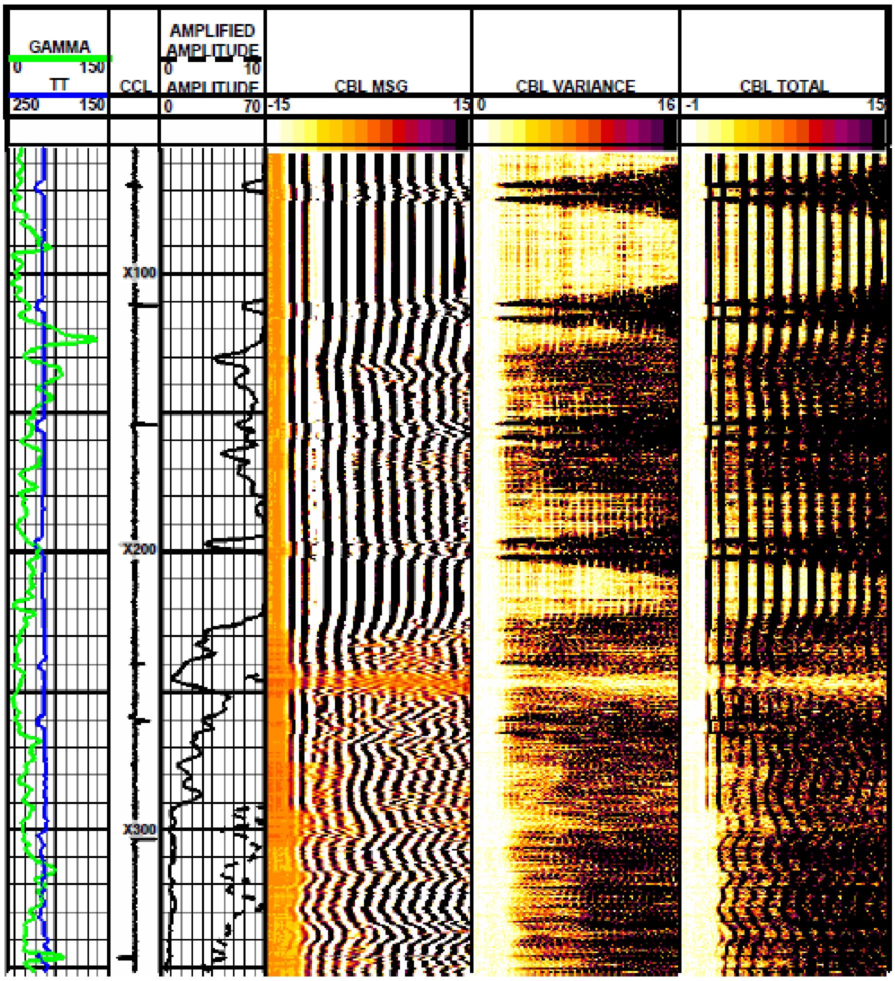

Figure 14: Example of ACE-CBL Log Presentation [16]

4.6.2 ACE for Ultrasonic Tools

Separating foamed cement from fluid is challenging due to their nearby and overlapping impedance values, but techniques have been developed to better evaluate the quality of foamed cement. ACE for ultrasonic tools is based on the the previously mentioned SVP to reveal the subtle changes in the structure of solids and fluids, more specifically to identify the crystalline structure of cement. On logs, the solid-free fluids will be recognized by a steady and consistent activity level while the cement, mixed with either fluid or gas, will exhibit a much more irregular activity level. The level of impedance activity is then calculated directly as a variance allowing minor changes in cement or fluid composition to be recognized, and a resulting variance image is generated. The method is used to distinguish cement from fluids and thus aids the challenging evaluation of foam cement. The fluid cut off value for the activity level, i.e. the scale at which variance is plotted, should be selected with care and be fixed for each specific tool. However, fluid cut off levels vary between different tool designs and thus between the different service companies, but it generally ranges from 0.15 to 0.45 [16]. The SVP based method does not use the impedance values directly to determine whether there are fluids or solids in the annular space, but only assumes that the cement is not consistent and consequently will exhibit irregular activity levels while fluids will yield low activity levels. However, as fluids also should exhibit low impedance values it is feasible to combine the SVP variance data with the original impedance values in order to determine whether fluids or solids are present in the annular space, i.e. the quality of pipe-to-cement bond. The combination of the two is presented by a cement image which is a binary presentation on a scale from zero to one that displays either cement or fluid (depending on user specifications) [16]. The variance image is unable to distinguish between consistent cement and water [16] and it is thus necessary to combine the variance results with original impedance data and favorably CBL data in order to correctly interpret the annular material. This underlines the importance of confronting available data together to avoid any misinterpretation.

4.7 Areas of concern

The downhole logging environment and its many parameters inflict complexity to cement bond evaluation. Factors affecting the logging tools together with different cement placement conditions should be well understood to avoid misinterpretation which in turn can lead to the unnecessary execution of costly remedial jobs. Below follows a brief description of some areas that must be understood and acknowledged when evaluating the cement quality.

4.7.1 Cement Channeling

Channeling is a partial bond condition where the casing circumference over a given length is only partly covered with cement. There are several contributors to channel creation during cementing and they are usually related to unfavorable displacement conditions, including (but not limited to):

- poor casing centralization
- failure to move the casing while circulating and cementing (pipe movement)
- dynamic solids settling from the mud or cement to the low side of the annulus (low side of the casing)
- free water separation from the cement slurry after placement (high side of the casing)
- fluid or gas entering the wellbore before the cement has set

The presence of channeling is indicated by a waveform that shows intermittent coupling of cement to the casing (casing response), but the same waveform could also indicate a microannulus. The only way to separate the two is by running a pressured and a non-pressured logging pass. If the casing signal remains unchanged when pressure is applied there is channellng, while if the casing signal disappears there is a microannulus present.

4.7.2 Microannulus

A microannulus is another partial bond condition where a gap of a few thousandth of an inch is present between the casing and the cement. Depending on the size of the gap it may cause the log to indicate partial bond to free pipe condition, though it is so small that the cement still can prevent any substantial volume of fluid to pass [18]. To determine if a microannulus is present

the casing is pressured up while logging so that the gap (if any) is closed and the pipe signal from the non-pressured logging pass disappears (illustrated by figure 41). Closing a microannulus with a *squeeze*[1] job is not feasible due to the small size of the gap. Hence it is important to separate channeling from a microannulus to avoid futile squeeze jobs.
There are six common scenarios in which a microannulus can be created [18]:

Thermal Microannulus: When cement cures it generates heat which can result in as much as 50 °F temperature increase depending on the cement thickness, slurry design, and thermal conductivity of the formation. After the cement has cured the generated heat will dissipate and cause the cement to shrink. This is a common phenomenon that frequently occurs when cementing a well, but applying 1000 psi of pressure while logging will usually eliminate the effect of a thermal microannulus.

Produced Microannlus: Pressure may be applied inside the casing after the cement has initially set, in order to test the BOP stack, liner top, or casing. When the pressure is released, the casing relaxes and a microannulus is created. In light of this it is recommended that pressure testing takes place immediately after the top plug seats on the bottom plug (bumping) when the cement is still in its liquid state.

Induced Microannlus: If mud is replaced by a lighter completion fluid, the drop in hydrostatic pressure can induce a microannulus.

Squeeze Annulus: When a cement squeeze job is executed there will be applied pressure to intervals of the casing to inject cement until a final squeeze pressure is obtained. When the pressure is released, the casing relaxes and a microannulus is created.

Constraining Forces: Cement about to set is subject to contraction and if there is a lack of sufficient restraining forces acting against the cement sheath, the cement pulls away from the casing and thus creates a microannulus. This is a common problem when cementing an interval consisting of unconsolidated sands or other soft formations. Heavy mudcake produced on any permeable formation can create the same situation.

Special Casing Coatings: The casing surface (for new casings) is covered with a mill varnish coating to protect the steel from rusting while in transit. The heat from the hydration process and the alkalinity of the slurry causes this varnish to melt and dissolve, respectively, which in turn leaves a small gap.

4.7.3 Cycle Skipping and Signal Stretch

Cycle skipping, as discussed earlier, increases the transit time and will depend on the threshold detection level of the tool and the shear strength of the cement. High shear strength cements causes the acoustic signal to become highly attenuated which in combination with an inadequate threshold value (usually less than 10% of the free pipe signal peak) will result in cycle skipping,

[1] Slurry is forced into the zone of interest by carefully applying pump pressure

i.e. the E1 amplitude is left undetected and the E3 (or even the E5) peak will be the first recorded amplitude as illustrated in Figure 6 on page 20. Cycle skipping is generally a result of strong formation signals, but because the amplitude levels are generally higher for these arrivals and thereby indicate rather pessimistic values with respect to bonding [16] it is important to identify the phenomenon. That being said, cycle skipping generally only occurs in bond logging and is indicated by a dramatic increase in transit time (when pressure is applied). Cycle skipping can also occur in liner overlap sections with high shear strength cement, i.e. the transit time can increase to the transit time value of the outer casing string [16]. Signal stretch is another phenomenon that can cause an increase (or delay) in transit time and it is caused by the attenuation of the pipe signal curve E1. The amplitude exceeds the threshold value yet it is attenuated enough to cause a slight increase in transit time (generally in the range of 10 to 12 microseconds). Signal stretch and cycle skipping are both illustrated in Figure 6 on page 20.

4.7.4 Tool Eccentricity

The eccentricity effect corrupts the accuracy of log interpretation and it is thus crucial to identify and adjust for tool eccentricity during the logging process. Tool centralization is important for both the sonic (CBL) and ultrasonic (CAST and USIT) tools while the SBT is less affected because of its favorable pad-configuration. In any case, the following guidelines for managing tool eccentricity are proposed and recommended [16]:

In case of tool eccentricity the CBL will experience a decrease in amplitude and an increase in attenuation rate which both will yield better bonding conditions. A quarter of an inch eccentricity for the CBL tool will for instance reduce the amplitude with approximately one half [16]. Another eccentricity effect is reduced transit time as the signal will be given a shorter travel path along the casing ID where the tool is closest (Figure 7, page 21). The latter is however useful as the transit time (TT) curve together with the log presentation is used to evaluate tool eccentering and thus also to validate the log quality. Guidelines suggest the following three criteria to be reasonable with respect to tool eccentricity for CBL [16]: 1) maximum decrease in transit time caused by tool eccentricity is not to exceed 4 microseconds, 2) logging tool resolution should be approximately 1 microsecond, and 3) the maximum range of transit time on the log presentation should not exceed one hundred microseconds.

If an ultrasonic tool is off-centered the signal will strike the casing ID at an angle that will prevent the signal from reflecting directly back to the transducer as intended. This will in turn give a distorted energy measurement and consequently a faulty representation of the cement quality [16]. However, because the ultrasonic tools have “better” properties than the CBL tool with respect to tool centralization (ultrasonic tools are shorter, stiffer, and lighter), the logs are consequently not as afflicted by tool eccentricity problems. Guidelines for maximum allowable eccentricity for the ultrasonic tools are nevertheless set to be 4% of the casing OD [16], but for the sake of the logs and the accuracy of cement sheath evaluation it would be advantageous to reduce tool eccentricity to a level as low as possible. Figure 15 clearly illustrates how tool eccentricity problems appear on a log presentation.

The adjacent green and dark areas in the impedance image track represents areas with very low and very high impedance values, respectively. This is obviously not the real case for the well, but are caused by impedance calculations being based on the wrong portion of the waveform.

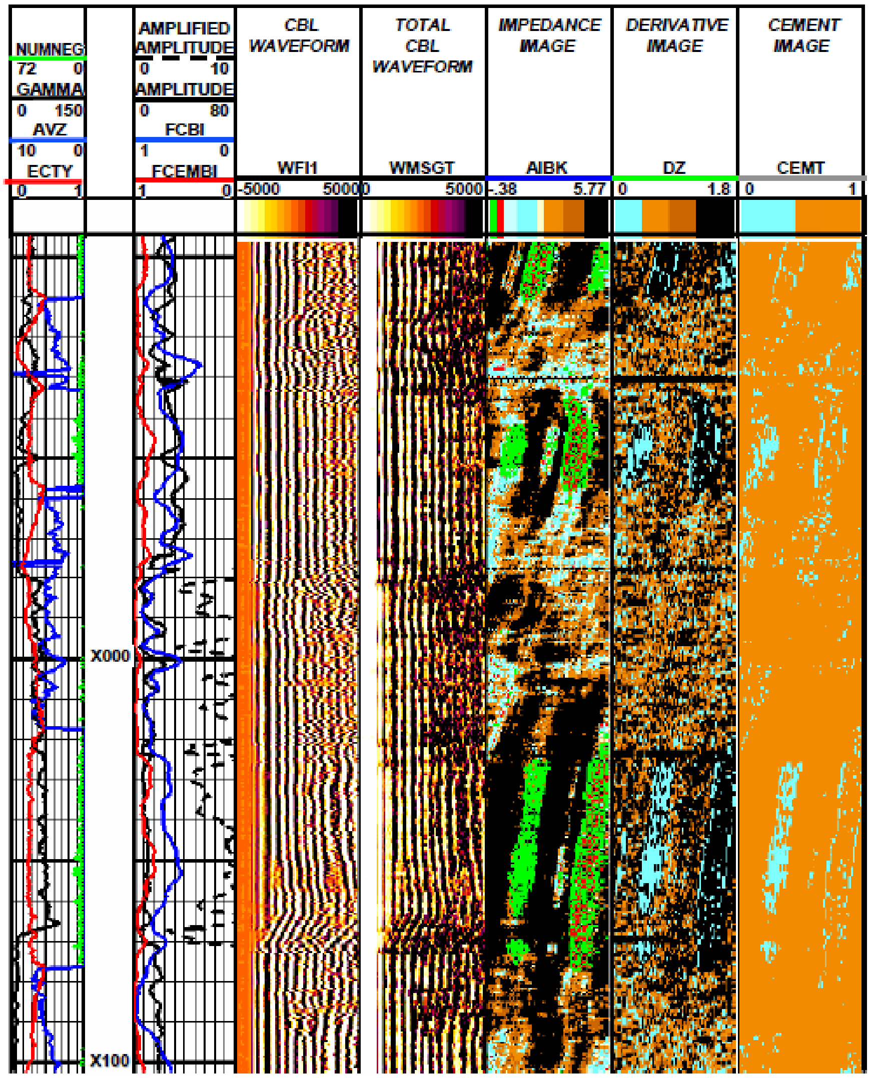

Figure 15: Tool Eccentricity Problem [16]

4.7.5 Thin Cement Sheath

The challenges with thin cement sheaths (less than 3/4 inches) have been described in more detail earlier and is also illustrated in Figure 5 on page 19. The important thing to mention, however, is that a thin cement sheath will, because of its reduced ability to attenuate a signal, provide a rather pessimistic presentation of the cement bond condition. For the ultrasonic tools a thin cement sheath will affect the impedance calculations and can be observed as “cat eyes” in the impedance image.

4.7.6 Formation Bonding

Formation arrivals are generally indicated on the VDL and MSG by clear, precise, reflected formation compression and shear waves [16] often with a wavy structure due to the heterogeneity of most formations. However, there are four situations down hole that can prevent these formation signals from showing up on the VDL or MSG at all, including:

1. Thick, soft and fluffy mudcake: If the mudcake on the formation is rather thick and consists of poorly compacted mud, the signal velocity through the mud will be so slow that the signal will not have time to enter the formation and be reflected back to the tool. Mudcake of this dimension will however decrease the hole diameter over permeable zones enough for it to be visible on an open hole caliper log.

2. Non-Cemented Hole Enlargement: If the hole is not properly cleaned (circulation time, pumping rate, pumping volume), cave-ins may be filled with drilling mud instead of cement and thus indicate poor cement to formation bond. If poorly bonded sections on the log correlates with the location of hole enlargements (obtained from the open hole caliper log) it is reasonable to believe that mud-filled cave-ins are responsible for the poor bonding. Mud-filled cave-ins may or may not cause problem for annular isolation.

3. Soft, or poorly to unconsolidated formations: Same as for the poorly compacted mudcake, the sonic velocity for soft and poorly to unconsolidated formations are diminished and the signal will not have sufficient time to enter the formation and return to the receiver within the measurement window. Soft salt, marine shales, fully unconsolidated sands, or anhydrite beds can give problems with log interpretation, but they do not generally present a problem for annular isolation.

4. Foamed or Gas Cut Cement: Cement subject to gas influx, whether intentional (part of design) or unintentional (from formation), will decrease density and thus also decrease the sonic velocity through the cement. Like for the previously mentioned scenarios, reduced sonic velocity inhibits the acoustic signal to travel into the formation and be reflected back to the tool within the measurement window. Gas entrapment in the cement sheath does not generally present a problem for annular isolation.

The four conditions mentioned above underlines the importance of obtaining knowledge on the logging environment in order to achieve an accurate log interpretation. Lithology, cement system, and details about the cleaning of the hole (circulation time, spacer volume, pump rate) are all data that contribute to the log interpretation process. However, neither the sonic or ultrasonic logging tools have the ability to discover channelling between the cement and the formation wall. Consequently the logs may indicate excellent bonding conditions in the annulus while in reality the annulus is not sufficiently isolated. If the latter case is suspected it can be investigated further by running a temperature log in combination with a noise log that are able to detect communicable flow between the cement sheath and the formation wall [16].

5.0 The Work Process

5.1 iCem®: 2D Hydraulic Simulations and 3D Displacement Simulations

Cementing a well imposes technical and operational challenges to the already complex wellbore architecture. The prerequisites to achieve a good cement job including all factors in need for consideration were discussed in *section 3.3*. The large number of factors and variable parameters involved require numerous calculations in order to arrive at a satisfying job design. To do so, Halliburton cement engineers utilize iCem® which is a powerful software program that helps assess the variables before, during, and after a cement job so that operational success can be increased and operational risk be reduced. The program consists of a set of simulators and calculators that allow parameters to be assessed individually and collectively so that best possible results are achieved. iCem® will provide the engineer with useful charts and tables to aid in job planning and optimization, and it can further yield more comprehensive models, including *two-dimensional fluid positions* and *three-dimensional displacement simulation*. Operational parameters such as e.g. standoff and hole-diameter will have considerable effect on the final job outcome, and iCem® helps to manage these variables, and to visualize the outcome so that different scenarios can be more easily compared. Amongst others, the program helps to:

- manage Equivalent Circulating Density (ECD)[1]
- manage pump schedule and the effect of dynamic temperature on fluid properties
- model the mud/spacer/cement interfaces over time with changing depths and wellbore conditions so that fluid designs can be optimized
- use rheological data including fluid compatibility tests and best-fit rheological models
- predict the amount of required spacer and cement volumes to avoid contamination and to achieve desired TOC
- determine optimum casing stand off to reduce the probability of channeling
- determine optimum pump rate for successful cement placement
- determine impact of pipe rotation and reciprocation to reduce the probability of channeling and achieve desired TOC

In order to grasp some of the complexity of cement job design, hydraulic simulations in iCem® have been carried out and are included below. The calculations are based on the actual parameters from the job discussed in case 1 in section 6.1, and demonstrates how the program can be applied to post-job investigations. Actual operating parameters can differ from the planned ones, so iCem® is applicable for examining the consequences of such changes.

[1]Effective density of the circulating fluid, expressed as the sum of static hydrostatic pressure and friction pressure from circulating

5.1.1 Simulations for Case 1

The cement job in case 1 (*section 6.1*) achieved very good results and the execution of it has been simulated and studied by means of the modeling software iCem® . Table 3 contains detailed information on the pump schedule while Table 4 shows the time schedule for the involved stages. Note that numbers to the left in Table 4 refers to the chart in Figure 16 that graphically presents the ECD and the hydrostatic pressure at all time from pre-job circulation until the plug has landed (bump plug). Both curves lie below the fracture pressure and above reservoir pressure gradient, which is necessary to avoid formation fracturing and to maintain wellbore integrity, respectively.

Table 3: Pump schedule for the cementing operation (Case 1)

Description	Stage No.	Density (sg)	Rate (L/min)	Yield (L/100kg)	Water Req. (L/100kg)	Volume (m³)	Bulk Cement (94lb sacks)	Duration (min)
OBM 1,43	1	1,430	2 300			0,000		0,00
OBM 1,43	2	1,430	2 300			160,000		69,57
Spacer OBM	3	1,690	2 300			25,000		10,87
Bottom Plug								
Gastight cement	4	1,920	750	75,790	36,87	33,900	1 049,05	45,20
Top Plug/Start Displacement								
OBM 1,43	5-1	1,430	2 300			3,000		1,30
OBM 1,43	5-2	1,430	800			102,223		127,78
					Total:	**324,123**		**254,72**

Table 4: Pump stages for the cementing operation (Case 1)

Graph Label	Time (min)	Stage Starts Pumping	Stage Enters Annulus
①	0	OBM 1,43	
②	45,8		OBM 1,43
③	69,6	Spacer OBM	
④	80,4	Gastight cement	
⑤	125,6	OBM 1,43	
⑥	177,1		Spacer OBM
⑦	210,3		Gastight cement
⑧	254,7	Plug Landed	

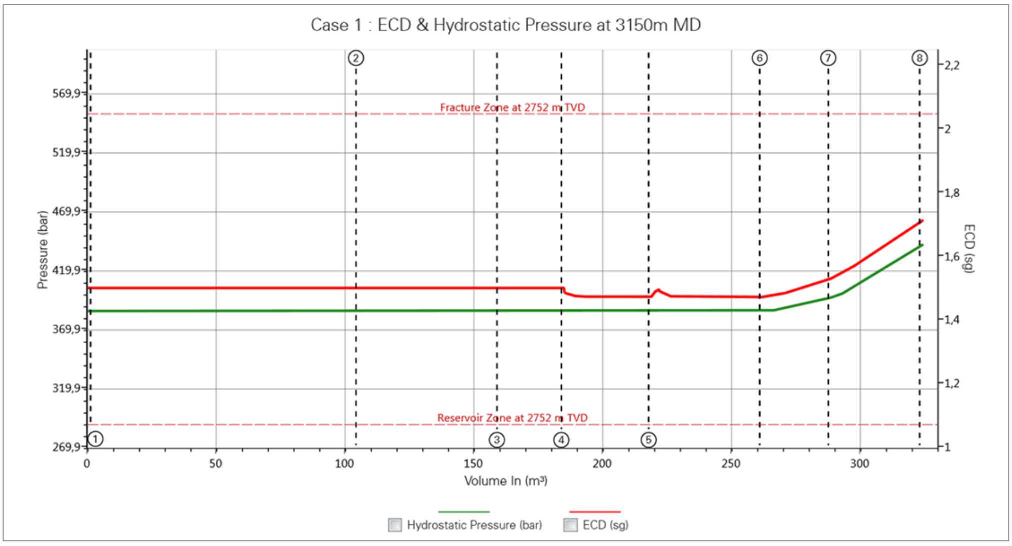

Figure 16: ECD and hydrostatic pressure curves during cementing

Figure 17 contains the calculated standoff profile based on gauge hole and a 90% requirement. There are no centralizers installed before 2161mMD, and the profile shows how planned standoff for the bottom section is equal to 95% (100% *at* each centralizer). This is rather good conditions and will lead to very good displacement efficiency at planned TOC (2198mMD). However, a hole is seldom considered to be 100% gauge and it is thus common to include additional calculations to account for larger hole than expected. In light of this, calculations based on 10% excess hole volume combined with a 85% standoff were carried out to illustrate how it will alter the displacement efficiency. The results are given in Figure 18 which shows the displacement efficiency at TOC for each of the three involved fluids. The calculated displacement efficiency is reduced from 95% to below 80% due to the altered conditions, which means that there will be a higher amount of spacer at this depth (TOC). The distribution of cement and spacer in the annular space at TOC for both scenarios are modeled in Figure 19 and offers an enhanced visualization of the displacement conditions. This model also shows how the additional presence of approximately 20% spacer appears on the low side of the casing which is the believed situation.

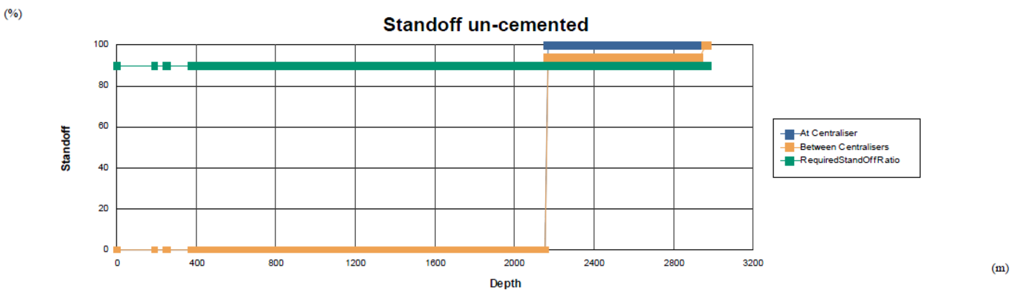

Figure 17: Standoff profile prior to cementing (95% planned standoff)

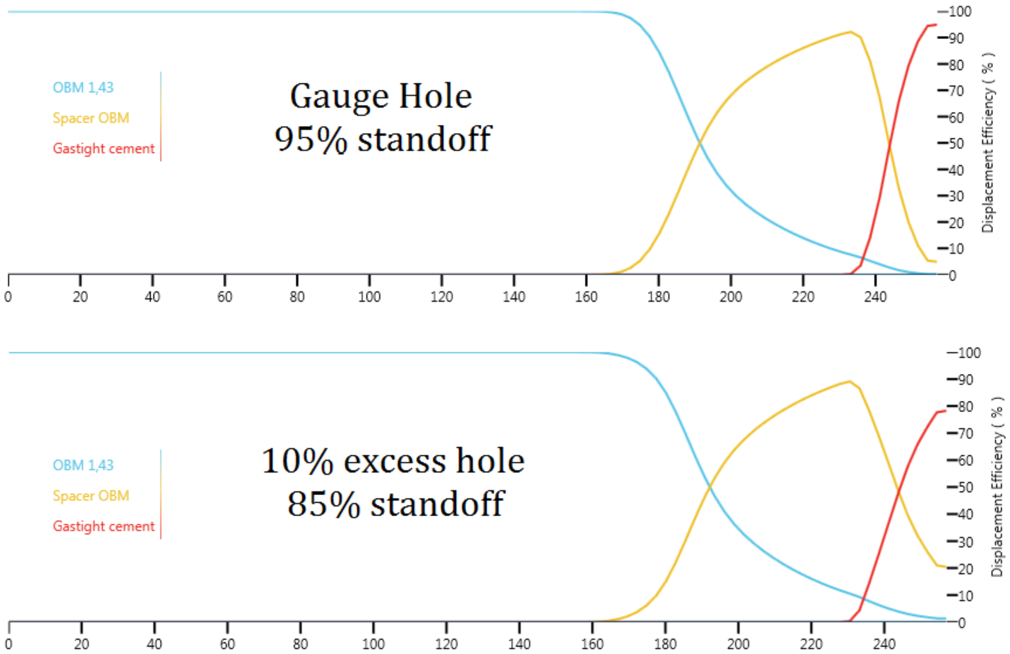

Figure 18: Displacement efficiency for the two scenarios at TOC

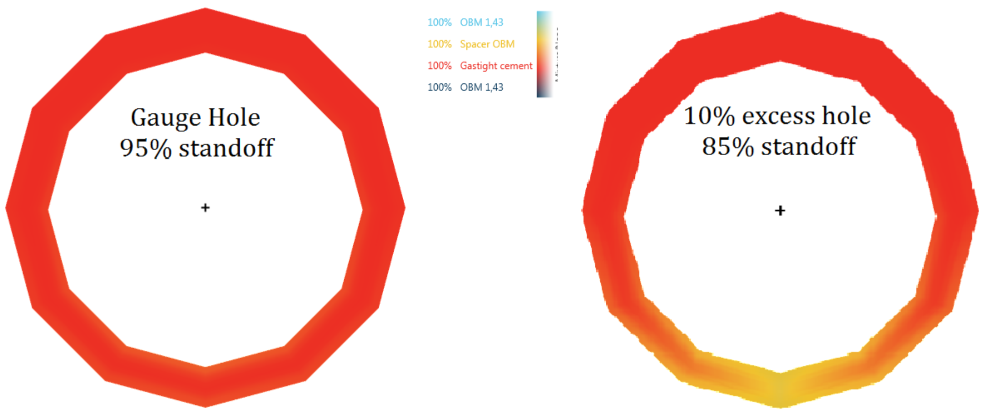

Figure 19: Cross-section of the annulus at TOC for the two scenarios

The models demonstrate some of the capabilities of iCem® as a modeling software, and the section in general gives a short introduction to how cement jobs are designed and simulated before being executed. There are numerous more sides to iCem® than approached here, which in general will allow a great number of different scenarios to be simulated, compared, and evaluated. In light of this, the calculations constitute a considerable part of the basis for job prediction, i.e.

the basis upon which cement bond logs accuracy are being questioned. This does not mean, however, that the models made in iCem® are fully accurate and finite with respect to the final job outcome. The calculations are naturally subject to some assumptions, while the wellbore conditions might introduce additional factors to the job that will alter the outcome, as illustrated in the previous 2-scenario example. Another model from this example is given in Figure 20, which again shows how there is reduced circumferential coverage around TOC. The 3D model (whilst in iCem®), allows for better visualization of troubled areas, like for instance where standoff is low and thus inhibits cement displacement on the low side of the casing. Standoff is increased to sufficient displacement efficiency is achieved, and a centralizer program for the casing is carried out accordingly.

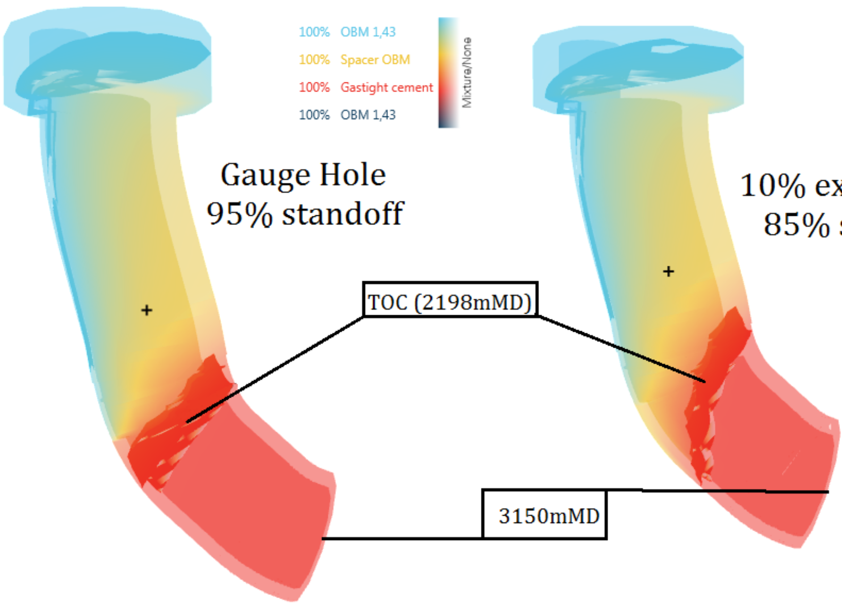

Figure 20: 3D fluid contours at the end of displacement for both scenarios

5.2 Log Interpretation

The following descriptions are included to ease the understanding of subsequent analyses and discussions. It should provide the necessary prescience to keep track when issues and comments are addressed back to the given log presentations. For further details regarding tool measurements and operating principles, the author would like to refer to section *4.0, Cement Evaluation*.

Cement Evaluation Tools

Basically there are two types of tools available for cement evaluation, namely sonic (conventional CBL/VDL) and ultrasonic (CAST and USIT). The difference between the two tool types is their signal frequency and output data, as discussed in *section 4.3* and *4.4*. Different service companies have developed their own versions of both tool types, but principle and output data are nevertheless similar between the different versions. The fluid-compensated SBT tool from Baker Hughes differs from the other tool versions as it utilize radial pads and high operating frequencies to measure the attenuation rate of the material behind the casing. The measurement principle of the

SBT resembles with that of sonic tool types and the SBT can thus be thought of as a branch rather than a separate tool type. Regardless of belonging, the most common tools utilized on the NCS are given in table 5 together with a brief description of their configuration and output data.

Table 5: Overview of common cement evaluation tools and their main output

Company	Tool Type	Principle[1]	Tool Configuration[1]	Main Output Data for Cement Evaluation
Halliburton	CBL	Sonic	Omnidirectional and Radial	Amplitude and waveform data
	PET	Ultrasonic (1.gen.)	8 stationary transducers	Average Impedance
	CAST	Ultrasonic (2.gen.)	Rotating transducer (250, 350, or 450kHz)	Acoustic Impedance Casing ID Casing Wall Thickness Waveform amplitude
Schlumberger	CBL	Sonic	Omnidirectional and Radial	Amplitude and waveform data
	CET	Ultrasonic (1.gen.)	8 stationary transducers	Average Impedance (behind casing)
	USIT	Ultrasonic (2.gen.)	Rotating Transducer (200-700kHz)	Acoustic Impedance Casing ID Casing Wall Thickness Waveform amplitude
Baker Hughes	CBL	Sonic	Omnidirectional and Radial	Amplitude and waveform data
	SBT	Ultrasonic (similar to sonic principle)	6 or 8 pads Compensated Attenuation	Signal Attenuation Rate

[1]*Note that tool details might differ between the mentioned companies and further that each company might have different models/versions of the same tool type. Tool basics will nevertheless be similar.*

Terminology and Scales

A log presentation consists of several *tracks* where data is displayed vertically with depth, as illustrated in Figure 21. Track 1 is the first track from the left, then follows track 2, but note that the narrow track usually displaying CCL (Casing Collar Locator) and/or depth data is seldom referred to as an individual track but rather considered as part of track 1. A track can display several curves of either the same data or of various data, like track 1 often contains curves for gamma ray (GR), transit time (TT), and eccentricity, but each curve is plotted on individual scales. The scale, color coding, and description of each curve are all given in the heading and should always be granted some attention before looking at the log data.

During interpretation the log data can (and will) be referred to by either the track number (e.g. track 2), the name of the track (e.g. CBL Waveform), or to a particular curve (e.g. WMSG). Each logging company will have their own characteristic way to display the log data by means of scales and color distribution, but the basic principle for interpretation purposes remains. A general recommendation is to always study the scale of each curve before judging the data, and the author would like to underline the following remarks:

- **Scales can have opposite directions**; some scales increase from left to right, while others decrease from left to right
- **Not all scales start at zero**; may have both negative and positive starting points
- **Color coding scale is not permanent**; the scale for each color palette can change even though the palette colors remain the same

- ***GR* and *GR API***; based on different calculations, therefore the values will differ based on whichever is used. This is, however, not of great importance as it is usually relative GR measurements that are of interest

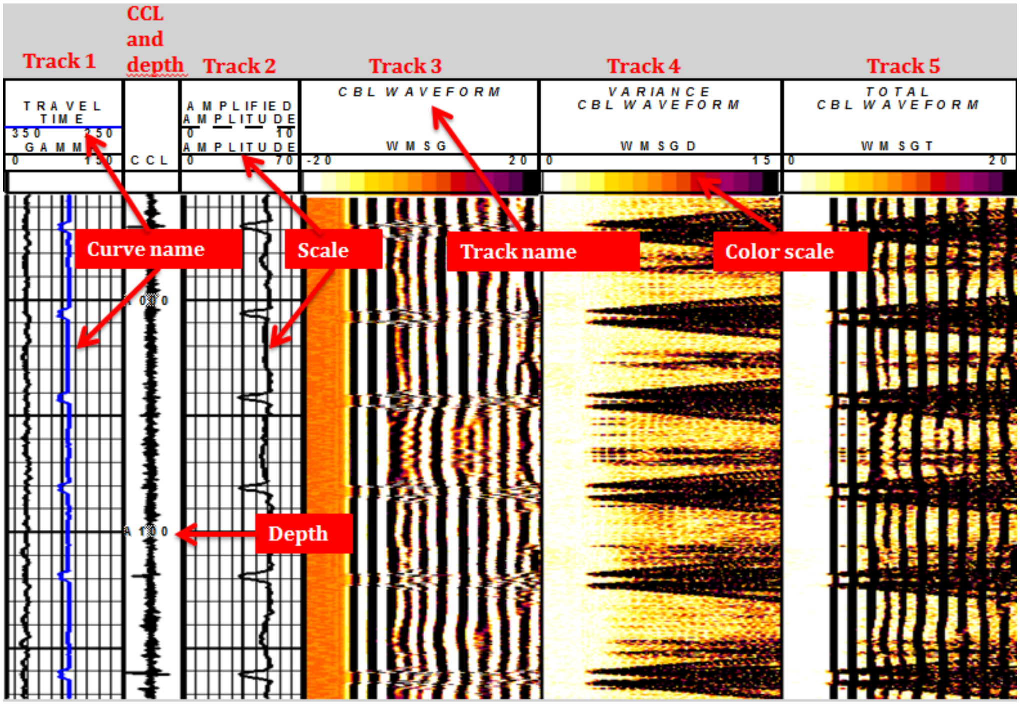

Figure 21: Explanatory log presentation

Influencing factors

Approached literature and perceived job experience during time of study consent that the joint process of cementing, logging, and final interpretation, is subject to a large number of influencing factors. Lack of clear and precise answers to difficult questions can lead to uncertainty and mistrust in methods used, which of course is unfortunate. As the work of this thesis involve finding plausible explanations and ease troubleshooting of anomalous cases, there is a need to clarify such influencing parameters and to learn how to cope with them. In light of this, an overview based on both internal(courses, discussions, reports) and external (published papers and experimental studies) sources are given in Table 6. The table is only meant to give a simple overview of the influencing factors and most of its content is discussed in more detail under section 4.0.

Table 6: Overview of influencing parameters

Description	Feature	Effect	Interpretation	Comments	Subject to effect
Wellbore Fluid	High Density	More attenuation[1]	Optimistic[2]	SBT not affected	CBL, amplitude
Cement Shear Strength	High or low shear strength	Attenuation directly proportional to shear strength	Both	Correct shear strength to be used as input	CBL, amplitude
Casing thickness	Thick casing	Less attenuation	Pessimistic	Valid thickness depends on the tool	CBL, amplitude
Thin cement sheath	<3/4"	Less attenuation	Pessimistic		CBL, amplitude
Tool eccentricity		More attenuation	Pessimistic	¼" eccentering → reduce amplitude with one half	CBL amplitude (*Ultrasonic tools not so afflicted by tool eccentricity*)
		Reduced TT	Not crucial	TT decreases with eccentricity	
High Impedance Mud (HIM)	High impedance value	Mud mistaken for cement	Optimistic	Mud-filled annulus mistaken for good bond. Easily identified by ACE.	Impedance map (USIT, CAST)
Signal Cycle Skipping		Increased transit time Generally higher amplitude	Pessimistic	Adjust detection threshold	CBL
Time Stretching		Increased TT		Not crucial	CBL
Microannulus	Few thousands of an inch thick	Less attenuation of casing signal (partial to free pipe)	Pessimistic	Pressure pass can help determine the presence. E.g. 0psi and 1000psi	CBL, amplitude
Lithology	Fast formations	Early formation arrivals (ahead of casing arrival)		Generally only possible when cement is bonded to both casing and formation	CBL, amplitude
	Unconsolidated formations	Washouts, cave-ins (mudfilled), oversized hole can affect standoff		Not necessarily a problem for zonal isolation	
	Unconsolidated formations	Washouts, cave-ins (mudfilled), oversized hole can affect standoff		Not necessarily a problem for zonal isolation	
Casing Overlap (Liner Lap)	Two concentric strings	Two sets of collars responses that look more like arrowheads than wedges. Arrowheads usually indicate microannulus.	Pessimistic if confused with microannulus	Outer collar response only visible when there is acoustic coupling between the two strings.	Variance CBL waveform (ACE)
Time of logging after cement job	Cement cure time	Sufficient time to be allocated for the cement to set	Green cement[3] would show less bonding	Wait for as long as possible. Conform with valid lab tests (UCA)	CBL, ultrasonic
Pipe cleanliness (inside)	Low side settling of sediments	Will affect log and may indicate a low side channel	Pessimistic	Run cleaning scrapers prior to logging	Ultrasonic

[1]*Attenuation is equivalent with lower amplitude readings. Less attenuation is thus equivalent to higher amplitude readings(see section 4.3.2 for more details).*

[2]*By optimistic it is meant that the feature/phenomenon will cause the log to show better bond/impedance values than the actual case, i.e. the subsequent interpretation will thus be too optimistic. Further, a too optimistic interpretation of the log will lead to overconfidence in the cement quality, which may be unfortunate. The opposite case is referred to as pessimistic, i.e. the log results will yield a too pessimistic evaluation of the cement sheath.*

[3]*Green cement refers to cement in its liquid form.*

5.3 Statistical Survey

The objective of this thesis is to search for any visible trends or plausible reasons to better explain what is believed to be discrepant logging results and evaluation of cement jobs. In light of this a statistical survey was carried out as part of the work. The survey is based on job reports, post-job reports, logs, and logging reports from 38 cement jobs performed by Halliburton within the last four years. The jobs have been logged by Baker Hughes, Schlumberger, or Halliburton, which in general have imposed some challenges with respect to data availability. Nevertheless, a number of operational parameters and factors have been gathered and sat against each other in the search for common trends.

In order to separate the jobs with good outcome from the jobs of poorer outcome, the study has divided the 38 jobs into four categories. Since *job* commonly refers to the cement job, this survey will from this point forward be referring to each individual item as a *case* rather than a *job*. Note that the 38 cement jobs now constitute 38 *cases*. A *case* will be the compound of everything from cement job execution and until final cement evaluation, and it will be classified accordingly. This means that each case is assessed based on cement job, logs, data quality, and final interpretation, and then classified according to how agreeing and veracious the data seems (qualitatively). The four categories are described as follows:

- Category 1 (green): This category contains cases with very good agreement between predicted job outcome and the final evaluation based on cement bond logs. No tool problems are observed and the cement job is deemed successful with confidence.

- Category 2 (faded green): This category contains cases where issues of minor character are observed, but none of of which have impaired the final judgement of the cement job. By *issues* it is meant the occurrence of one (or more) of the following: 1) problem with logging tool and/or poor data quality due to e.g. debris settling, mud weight, thick casing, or 2) intervals with partly bonded cement that lack convincing isolation capacity, e.g. patchy bonding, channeling, microannulus.

- Category 3 (faded red): This category contains cases where observed issues are of a more significant character that have somewhat impaired the ability to evaluate the cement job. Despite of the experienced trouble the cement jobs have still been possible to evaluate and are not of fatal character.

- Category 4 (red): This category contains cases where the cement job has been evaluated from medium to poor with barely no isolating capacity, and which in many cases have triggered some sort of post-job investigation. Results have raised uncertainty with respect to the logging tools ability to adequately evaluate the quality of the cement in place.

5.3.1 Final Overview

The case studies in *section 6.0* include at least one case from each category to provide more detailed insight to the characteristics of each category. As mentioned, the purpose of the categorization is to simplify the search for patterns among the input parameters. This being said, the author acknowledges that the sample size is not of substantial character and should rather be considered inadequate with regards to establish any finite trend. However, the overview is meant to guide further investigation and hopefully eliminate or throw light on certain factors. Any trend found has to be investigated further in more detail before making a clearer conclusion and it should preferably be confirmed within a larger sample population. The overview is given below in Figure 22

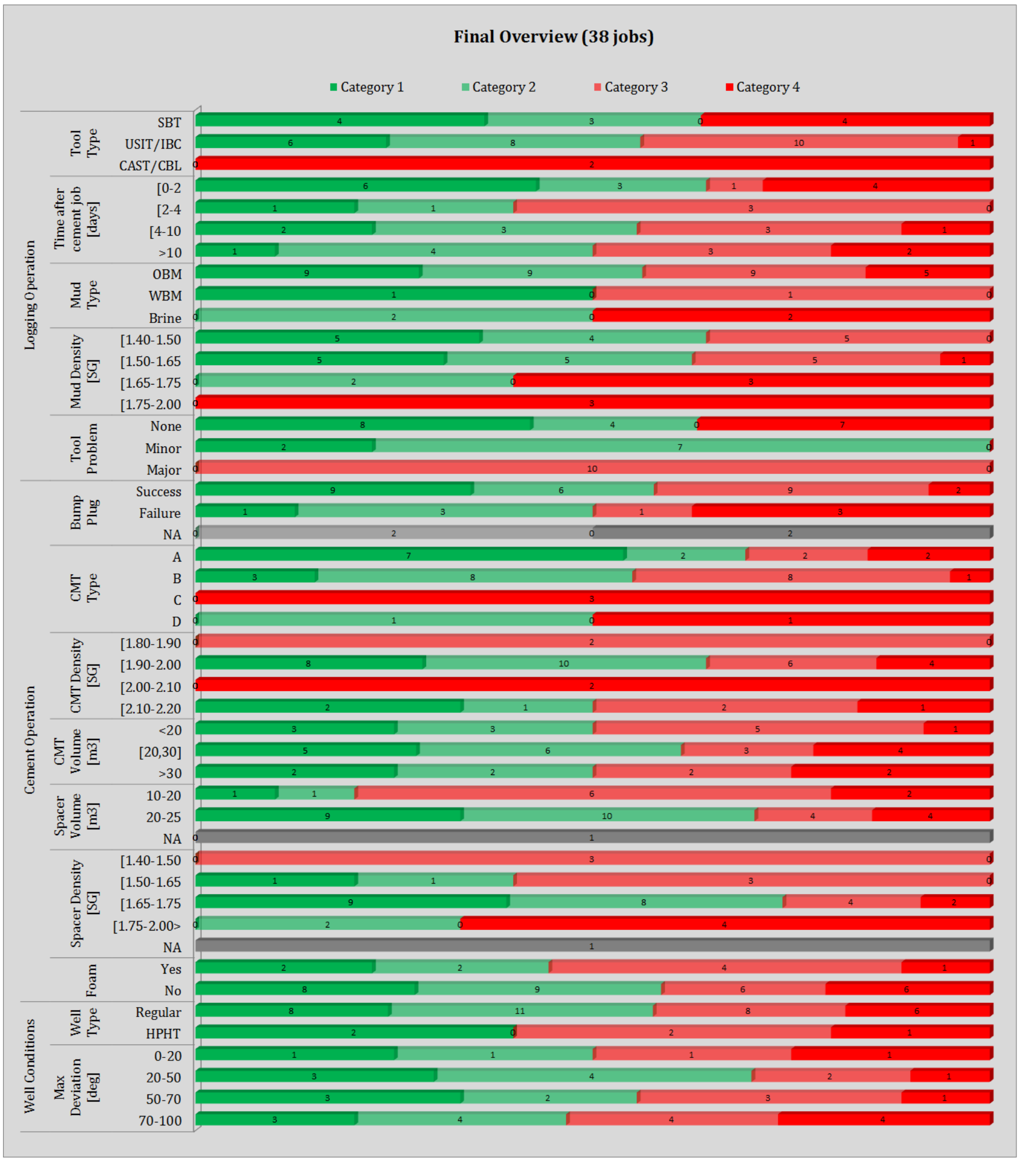

Figure 22: Overview of selected parameters from the 38 jobs studied

Comments

The chart in Figure 22 provides an overview of the four categories and how they distribute themselves for each given feature (or numbered interval). The vertical axis contains the various factors (features) studied, where some have been divided into sub-intervals to better be able to reveal any existing pattern. Along the horizontal axis the distribution of the four categories from one to four are presented together with suitable colors. The colored bars will allow for particular troublesome parameters to be discovered rather quickly as the red color will then extend from right to left and be the dominating color. The number inside each bar is the amount of cases and is included as a relative measure to avoid misinterpretation of the data. For instance, by looking at Tool Type; 100% of the jobs logged with the CAST tool belong to category 4, while only 36% of the jobs logged with SBT belong to the same category. But by approaching the numbers the CAST has only two jobs that belong to category 4 while the SBT has a total of four jobs in this category, i.e. twice as many. This short example shows that there are two ways to approach the data: 1) look and compare the percentage distribution within each feature/ interval, or 2) look and compare finite numbers within each feature/interval. Because the total sample size of 38 jobs is relatively small compared to the scope of the addressed problem, a joint approach is taken to avoid faulty and biased conclusions. Some cases failed to come up with data on certain features and have therefore been classified assigned to the feature NA (Not Available) and given a grey color in the chart.

5.3.2 Observations

When it comes to the slurry design there is one particular kind distinguished from the rest, namely *CMT Type C* which is considered to be a non-conventional cement type. This particular cement type is an elastomeric cement with relatively light weight and ductile behavior which generally presents additional challenges to bond logs and bond log interpretation (depending on the type of logging tool) [11]. For CBL it is mainly the low shear modulus which imposes a problem since the primary cement variable to affect attenuation is precisely the shear modulus. This cement type will not be able to attenuate the casing signal as much as a conventional class G slurry with same density even though the cement is properly bonded to the pipe and hydraulic isolation is established [11]. Hence, conventional interpretation methods are not applicable for such non-conventional slurry designs. Further, it is neither considered applicable to develop separate charts (like the one in Figure 4 on page 18) for elastomeric cements due to their highly variable nature and sensitivity to design changes [11].

For ultrasonic tools, which measure impedance and consequently become sensitive to cement density and velocity, problems will arise when cements with low velocity and density are to be evaluated because their impedance values will decrease and may overlap with water (and even approach the value for gas). For the *CMT Type C* discussed here the densities are relatively high and should not be a problem, but they still have an elastomeric behavior which will reduce the velocity of sound through the cement and thus yield low impedance values. The low impedance introduce a possibility for the cement to appear as fluid on the impedance map which consequently inflicts uncertainty to the interpretation; which together with low shear and low attenuation on the CBL signal may induce wrongful interpretation of actual conditions. ACE analysis is however capable of capturing the subtle variations between cement and fluid, as presented in *section 4.6*.

For the SBT, the tool configuration will eliminate effects from borehole fluid, but the measured attenuation rate is still dependent on the shear modulus of the cement and will thus be affected by the lower strength of this slurry (*CMT Type C*). Calibration/interpretation charts for cements with lower compressive strength (lower shear modulus) are developed for the SBT and can be applied to the logging process. However, as cement strength decreases the expected attenuation rates of the cement decrease as well which will result in a significant reduction in the dynamic range between free pipe and bonded pipe, i.e. the expected attenuation rates for free pipe and bonded pipe becomes closer. Such reduction in dynamic range introduces uncertainty to the final log interpretation in the same way as lower impedance values bring uncertainty to the ultrasonic impedance measurements. Work is, however, being carried out to increase this dynamic range by amplifying the signal strength through the casing so that attenuating factors in the wellbore (casing, cement, fluid) can be more accurately distinguished.

The survey revealed a surprisingly high amount of jobs where some sort of problem was experienced with the logging tool. Of the 38 jobs studied, one half is subject to some sort of issue with the logging tool. The significance of these problems varies and is not always found to be crucial to the final interpretation, but in some cases the data quality is so poor that it cannot be used at all. 10 out of the 19 jobs with tool issues are considered to have impaired the final ability to evaluate the cement job. For the latter case it is typically the ultrasonic USIT tool that is subject to problems, and it is usually because of the drilling mud, the casing thickness, or the lack of a clean surface inside the casing (or a combination of the three). Note, however, that the USIT tool constitutes nearly 60% of the surveyed data and is thus more heavily presented than the tools from other service companies.

USIT problems reduce the quality of azimuthal data which is unfortunate when it comes to establish whether or not zonal isolation can be expected. To recap, the CBL/VDL is omnidirectional and will only yield average data from the casing periphery which will not always be sufficient to identify channeling in the cement (and consequently not zonal isolation). So, since the USIT is the only measure to give azimuthal data, any problems that impair data quality is without doubt negative to cement evaluation. Impaired data causes a conservative approach that consequently might give a too pessimistic interpretation of the cement quality. The found portion of jobs subject to tool issues should naturally give rise to some concern with respect to the tools ability to yield accurate data for cement evaluation. But at the same time it is important to acknowledge that the tools have also shown their ability to recognize whenever poor data is recorded and thus avoided any interpretation made on wrongful/poor data. The combination of tool eccentricity and high mud weight is for instance very unfortunate to the USIT, but it is also relatively easy to discover. In light of this, the extent of discovered tool issues should give confidence in the quality checks that are carried out during the logging operation and afterwards. However, tool issues that impair azimuthal data and compromise cement evaluation are unfortunate and should be avoided.

6.0 Case Studies

This section contains 5 cases that have been studied in more detail and included to provide the reader with knowledge on how the cases entered in the statistical survey have been categorized. For each case there will be given a short case summary as an introduction closely followed by a comment to data quality. At the end of each case the reader will find some selected intervals that the author has found interesting for that particular section. The given log presentations will vary in appearance between cases because of different service companies involved, but descriptions and explanations are given in the text and should be sufficient to keep track. If descriptions are found to be too shallow or puzzled the author would like to refer back to previous sections. Especially section *5.2 Log Interpretation* should be consulted as it contains useful information regarding scales and terminology.

6.1 Case 1: Category 1 - Green

6.1.1 Case summary

This case has been assessed as a category-1 case due to solid agreement between expected job outcome and final cement evaluation based on USIT/VDL data. The near 3000m long 9-5/8" production casing was cemented in place using a conventional 1.92SG slurry (*CMT Type B*) with no losses observed. Maximum deviation of the section is 71 degrees from the vertical, the previous casing shoe is at 1863mMD[1], and theoretical TOC is at 2198mMD. The logging pass was run the day after cementing and yield excellent bonded cement with high impedance values around the entire pipe with only minor incidents of lower impedance cement on the low side. Near 900m of the 1240m logged interval show good bond with expected isolation capacity, and the overall data quality is very good.

6.1.2 Data quality check

Both the USIT log and the CBL/VDL yield high quality data with no sign of performance outside recommended specifications. The quality check for the USIT is similar to that of CAST involving tool eccentricity, collar response, radius measurement, amplitude measurement, and also its general correspondence with the CBL/VDL data whose quality have been validated by transit time and free pipe amplitude. Note that the heading (with scales) for all logs in this case is presented in Figure 23 and consists of 12 vertical tracks.

Figure 24 shows a 24-meter segment extracted from a 70m free pipe pass to validate tool response. The free pipe pass shows good correlation between the casing collar detectors (CCLU, track 1), increased impedance values (track 8-11), TT curve (track 12), and finally the chevron patterns in the waveform data (track 12). Further, the TT curve (track 12) appears as a straight line with minor increases only at each collar, and the waveform data (track 12) show strong casing signal. A repeat pass was carried out and shows good correspondence; overall tool response is good and data is considered adequate.

[1]MD = Measured Depth; the length of the wellbore path

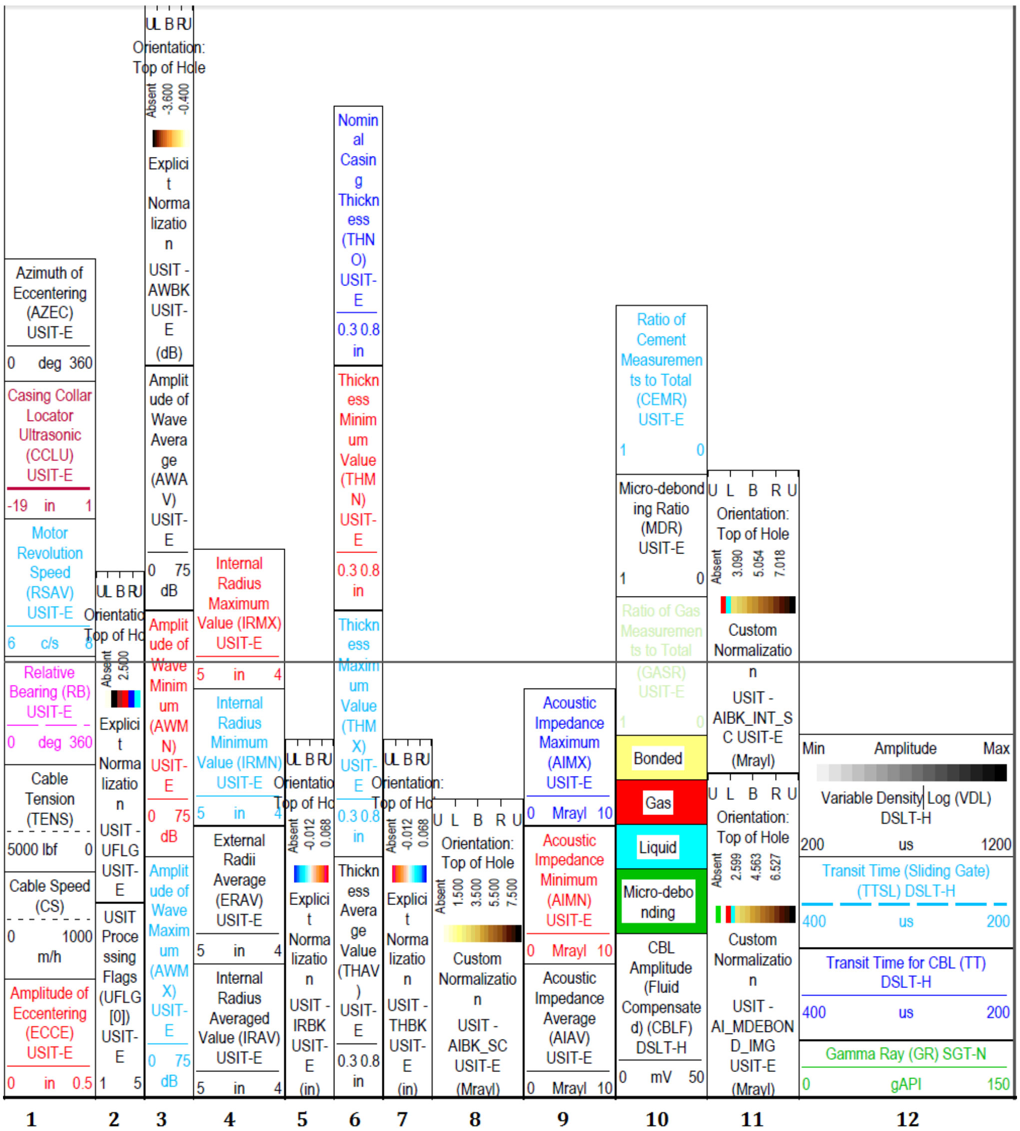

Figure 23: Heading with track description and scales for the USIT data

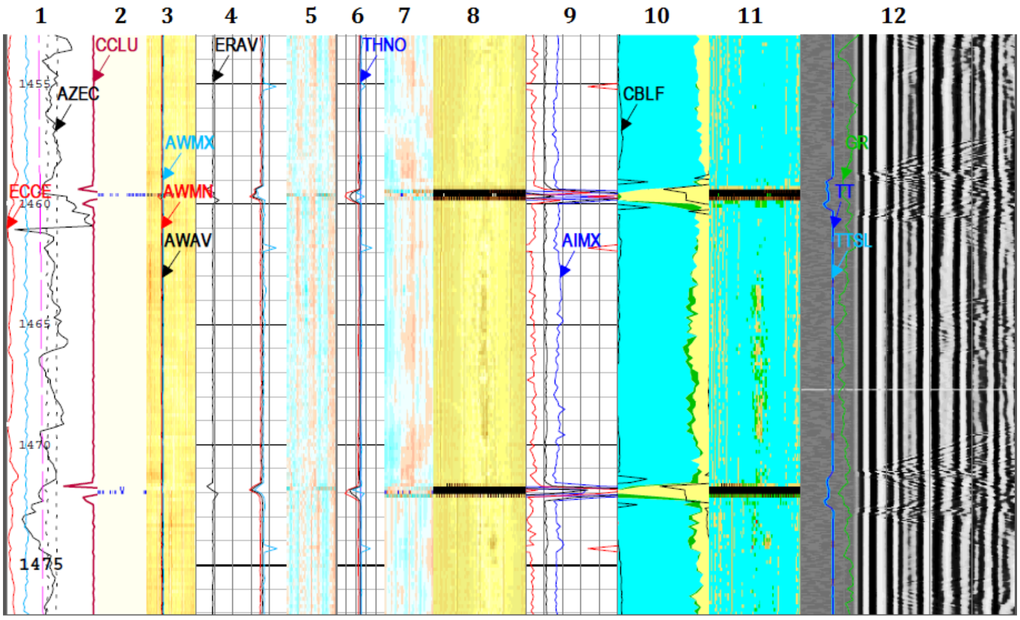

Figure 24: Free Pipe pass to validate tool response (section: 9-5/8" liner, interval: 3875mMD-3879mMD)

6.1.3 Sections of interest

Eccentricity effect (1955mMD-1960mMD)

Figure 25 present a small segment with a sudden drop in impedance which most likely is caused by tool eccentricity. The red eccentricity curve in track 1 undergo significant increase at the same depth (1955mMD) where the average impedance data drops from about 3.5MRayls to 2MRayls, indicate by cyan in track 10. Note that even though the heading of track 10 reads 'bonded' for the yellow color it does not mean that the pipe is bonded with cement. The coloring is extracted from impedance calculations and is most likely due to high impedance mud and/or spacer in the annulus. The amplitude in track 10 is still high (about 40mV) and the VDL (track 12) shows strong casing signals.

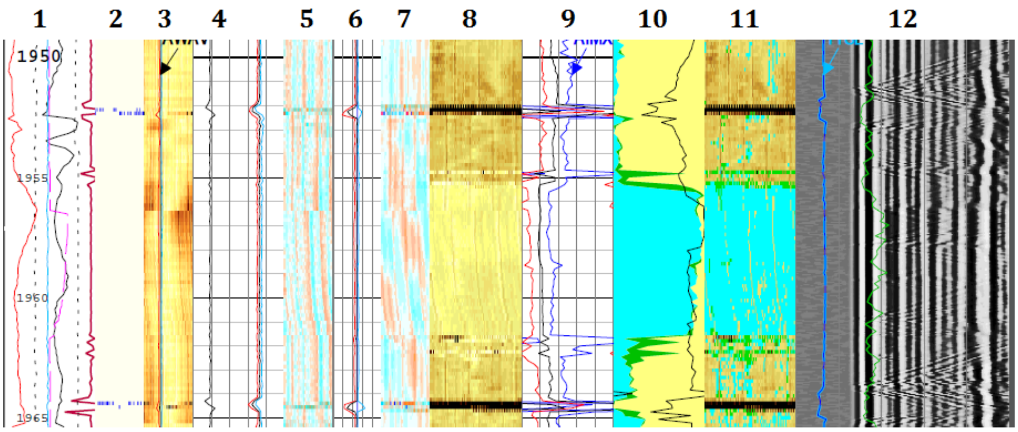

Figure 25: Minor eccentricity problems observed from 1955mMD-1960mMD (section: 9-5/8" casing, full interval: 1950mMD-1965mMD)

Transition zones

Transition zone 1(1980mMD-2025mMD): The selected interval in Figure 26 shows a transition zone where annular impedance undergo minor increase while the measured amplitude suffers a small decrease. The log hence suggests that higher impedance material with more dampening effect is present in the annulus, which most likely is the weighted spacer.

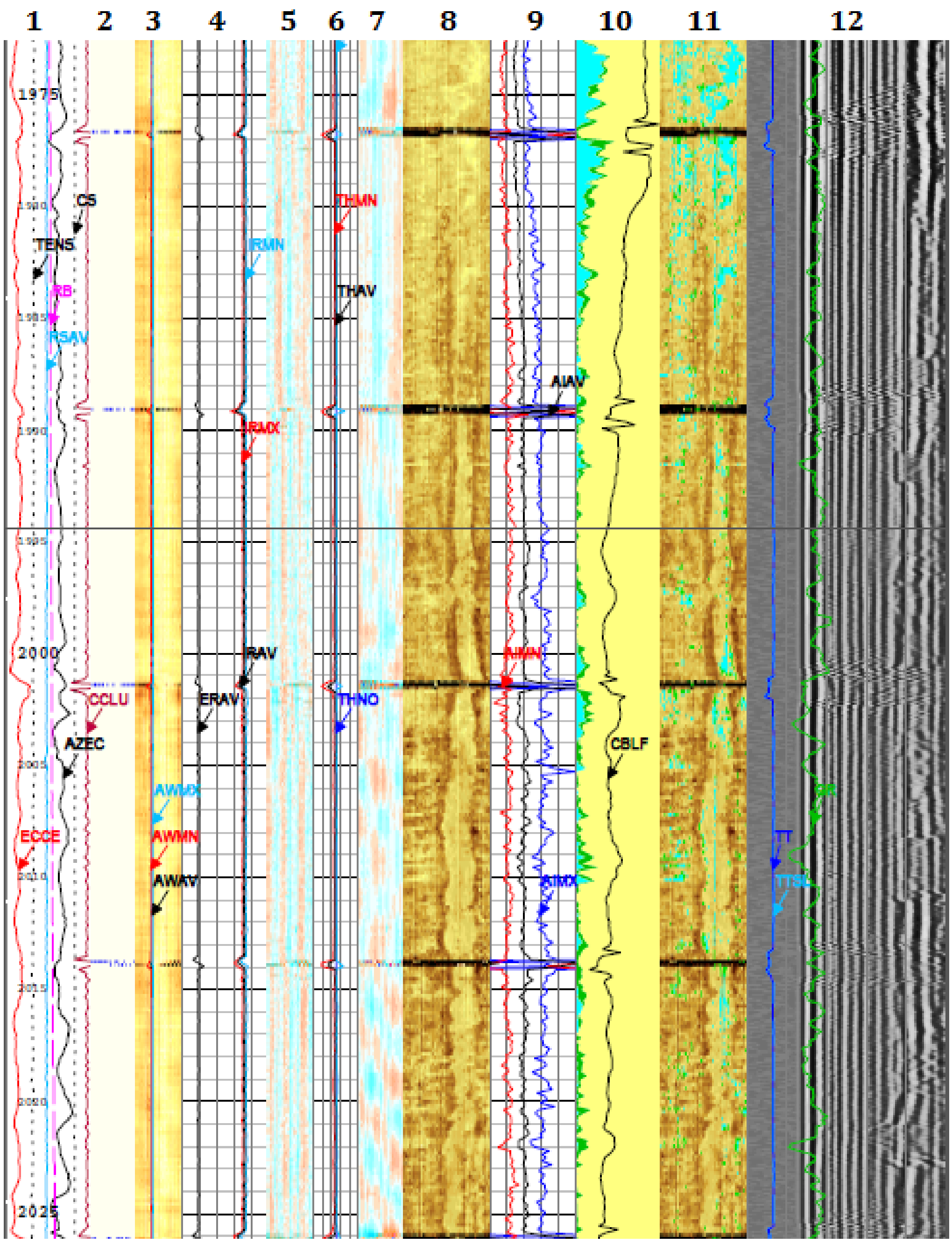

Figure 26: Transition zone 1 with increasing impedance and decreasing amplitude (section: 9-5/8" casing, interval: 1980mMD-2025mMD)

Transition zone 2 (2055mMD-2075mMD): The selected interval in Figure 27 shows a transition zone where impedance increase to a new highest level while the casing signal becomes less visible. The amplitude is also approaching a very low and stable value below 10mV. However, based on the impedance image in track 8 it appears to be a channel on the low side of the hole with generally low impedance. It is not expected for this interval to yield zonal isolation conditions.

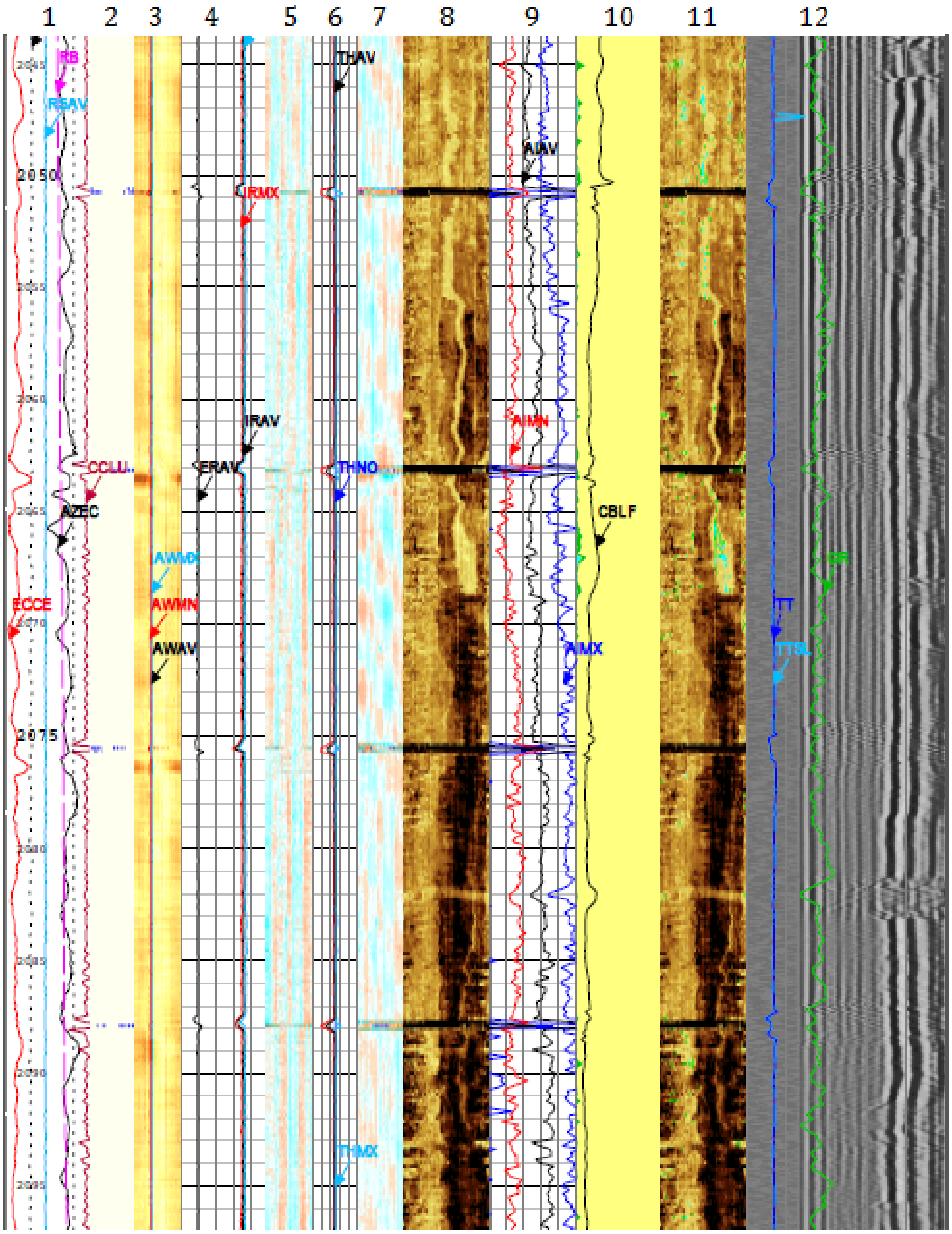

Figure 27: Transition zone 2 with further increasing impedance and decreasing amplitude (section: 9-5/8" casing, interval: 2055mMD-2075mMD)

Well-bonded section (2165mMD-2210mMD)

The selected interval in Figure 28 shows a near 50m long interval with high impedance cement bonded around the entire casing periphery. Impedance curves in track 9 yields an average value between 8 and 10 MRayls throughout the entire interval, while the close spacing between the maximum and minimum curve indicates good circumferential conformity. Note that when the (blue) maximum impedance curve (AIMX) frequently shifts from being visible on the right and left side in track 9 it is not a tool or data problem but simply a scale extension; when the value exceeds the scale maximum to the right, which is 10mV in this case, the curve will re-appear on the left and continue recording from 10mV and up to 20mV (for this particular scale).

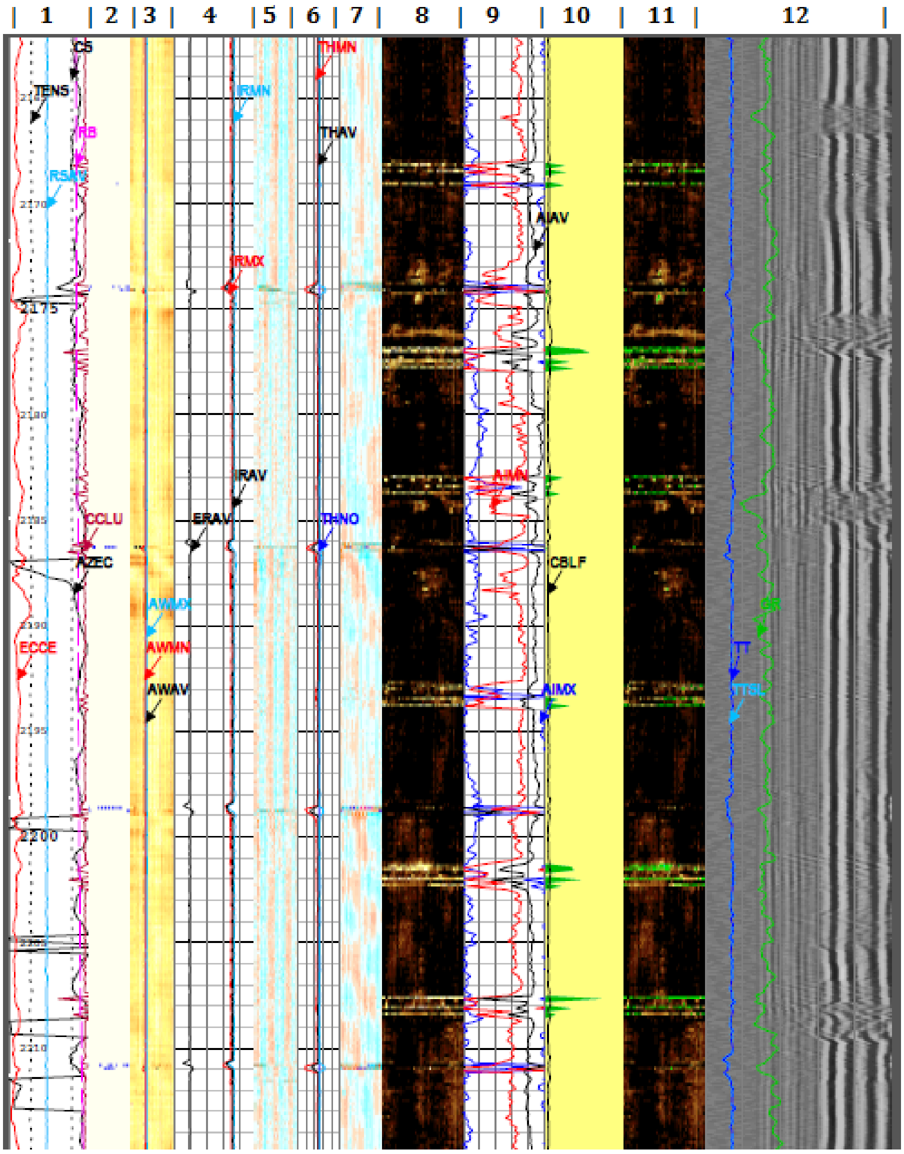

Figure 28: Well-bonded section with high impedance cement (section: 9-5/8" casing, interval: 2165mMD-2210mMD)

6.2 Case 2: Category 2

6.2.1 Case summary

This case has been categorized as a category-2 job due to minor problems with the tool during logging. The tool problems caused some areas with poor data which was impossible to interpret, but because of other areas with good quality the cement job could still be interpreted with confidence. The 9-5/8" liner was set at 3708mMD and cemented in place with conventional 1.90 SG slurry (*CMT Type B*) with a theoretical TOC at 3215mMD (TOL[1]). The liner was logged 26 hours later with a combined USIT/CBL tool, and overall the cement bond is found to be very good for the sections with good quality data. Two logging passes were performed with a scraper/clean-up run in between to try to overcome the tool problems which were believed to be caused by internal deposits (debris inside the pipe). There was also a problem to run the tool down to the liner because of internal blockage, probably cement residuals. Improvements in general were seen on the second log run and the tool was run even deeper, but the tool was affected by internal debris towards the bottom of the liner. Final interpretation shows a short section (11m) at the top of liner with medium bond, while the rest of the liner is found to have good cement bond with expected isolation. A minor decrease in bond quality from good to medium was seen between the first and second log run for the liner lap section. It is suspected to be caused by cement shrinkage due to lack of free water source in this section and consequently the birth of a microannulus.

6.2.2 Data quality check

To validate the quality of USIT data measured fluid velocity with depth is used to compute the average internal radius of the pipe. For this run the average radius was a little high compared to the nominal value for this type of casing which suggest a small error in measured fluid velocity. Fluid impedance is another measure to validate that the USIT tools are reading the right values, and in this case the measured values were outside the expected range. Hence, theoretical high and low impedance values were computed to yield both optimistic and pessimistic values for comparison, respectively. The resulting values had, however, very little impact on final interpretation and are not considered crucial to the final interpretation. Tool eccentricity is within specifications for the USIT and overall quality is good. The exception is some internal debris towards the bottom of the liner (3377mMD-3386mMD) which is believed to prevent the transducer head to rotate properly. The problem remains during both log runs and results in un-interpretable USIT data for the bottom section. The CBL data shows minor variations in transit times which indicate some tool eccentricity, but the overall quality is still considered good and there is correspondence between the USIT and CBL data. The repeat sections match the main logs as well. Note that the heading with track numbers given in Figure 29 is common for all log presentations in this case, and should be confronted for scales and track descriptions.

[1]Top of Liner

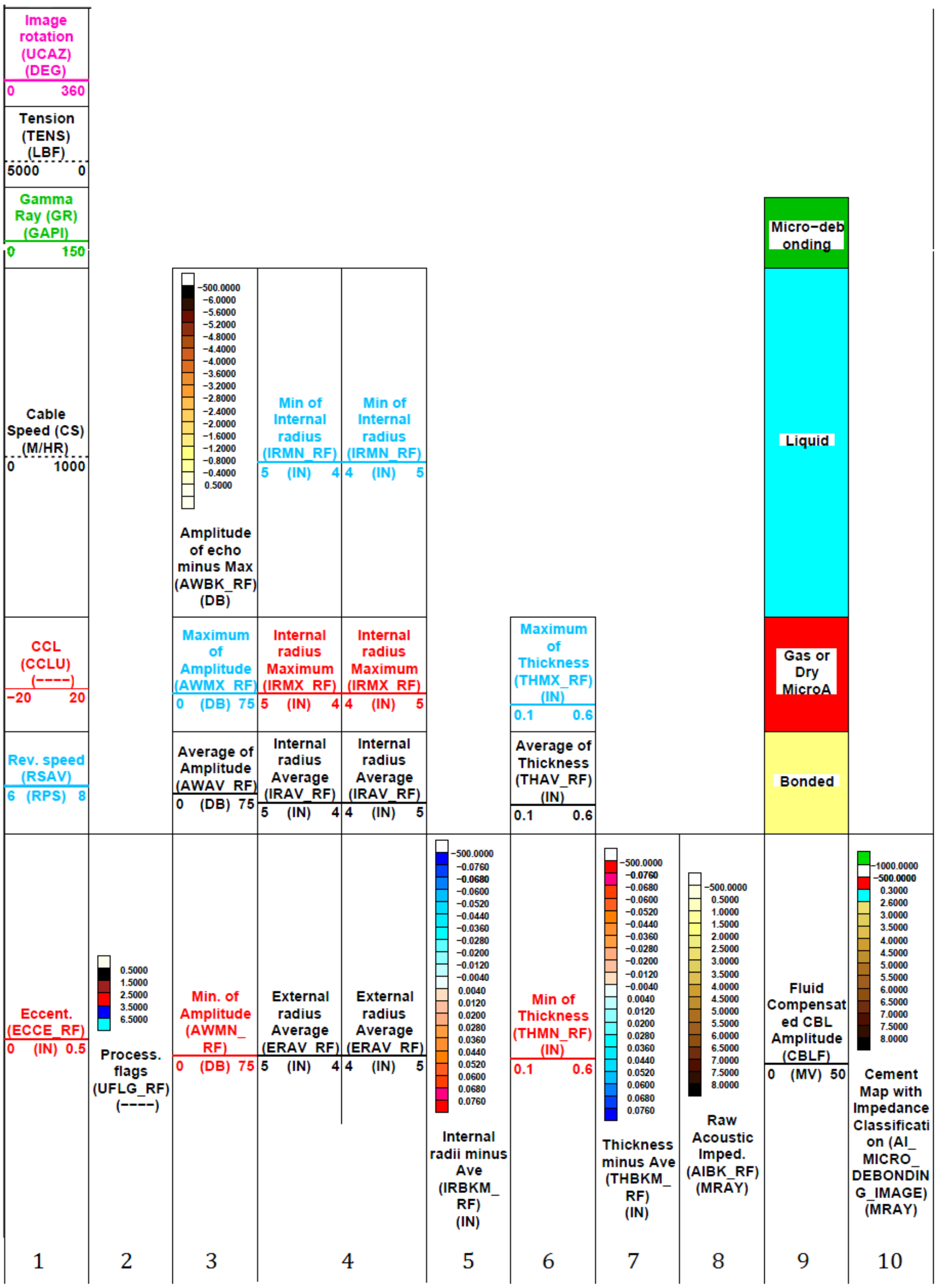

Figure 29: Heading with track description and scales for the USIT data

6.2.3 Sections of interest

Poor USIT data from the 1st log run (3375mMD-3385mMD)

Figure 30 shows the bottom 15 meters of the logged interval with very clear signs of tool problems. Processing flags are flooding track 2 which indicate internal debris. The casing cross-section image in track 4 becomes more narrow towards the bottom which also suggest internal debris. Overall, this USIT data is not usable for interpretation purposes.

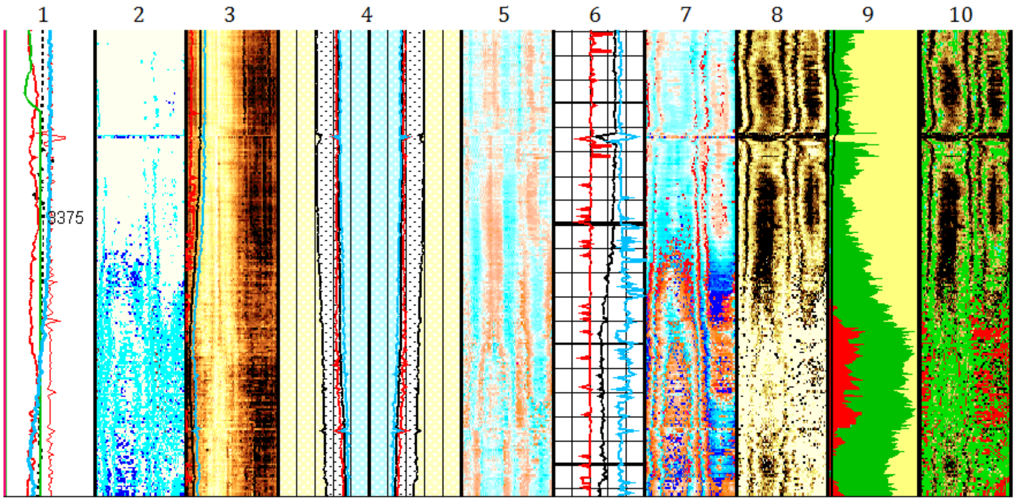

Figure 30: Small section with very poor USIT data (section: 9-5/8" casing, interval: 3367mMD-3386mMD)

Deteriorated bond in liner lap (3244mMD-3271mMD)

Figure 31 shows a near 75m interval at the same depth from the two logging runs carried out approximately 16 hours apart. The scales between the two runs, which here are separated by a red line with the first log run to the left, are equal and allow a direct comparison of track data. By comparing the two logs there is a clear deteriorating tendency with time between 3244mMD and 3271mMD which is believed to be caused by cement shrinkage, as mentioned earlier under *case summary*. Track 9 contains the amplitude curve and is barely visible on the first run (low value), while it becomes more high-lying on the second run. The impedance data in tracks 8 and 10 shifts from being dark and consistent to less dark with elements of green on the low side, which indicate de-bonded solids. Overall the log comparison between the two runs is indicative of bond deterioration, but only for this specific interval.

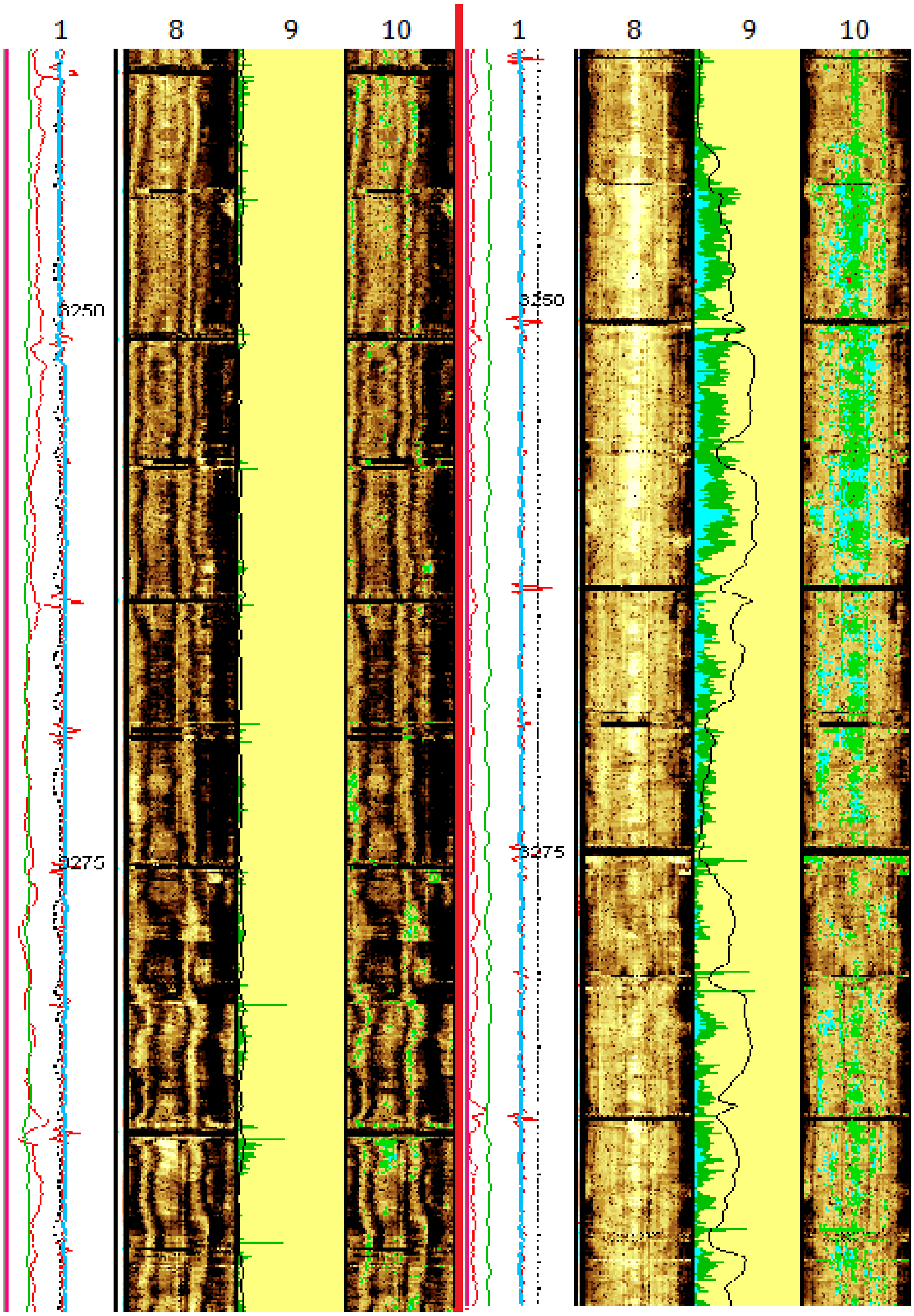

Figure 31: Log comparison from first (left) and second (right) log run that shows bond deterioration with time (section: 9-5/8" casing, interval: 3230mMD-3295mMD)

Well-bonded section (3474mMD-3526mMD)

Figure 32 shows approximately 50 meters of well bonded cement in the annulus. The recorded amplitude in track 9 is barely visible as it is very low, and the impedance data in track 8 and 9 are indicative of good bond around the entire pipe. The VDL data in track 11 show barely visible casing arrivals together with trace of formation signals which both are indications of good cement bond. Overall this section yield good quality data for cement evaluation.

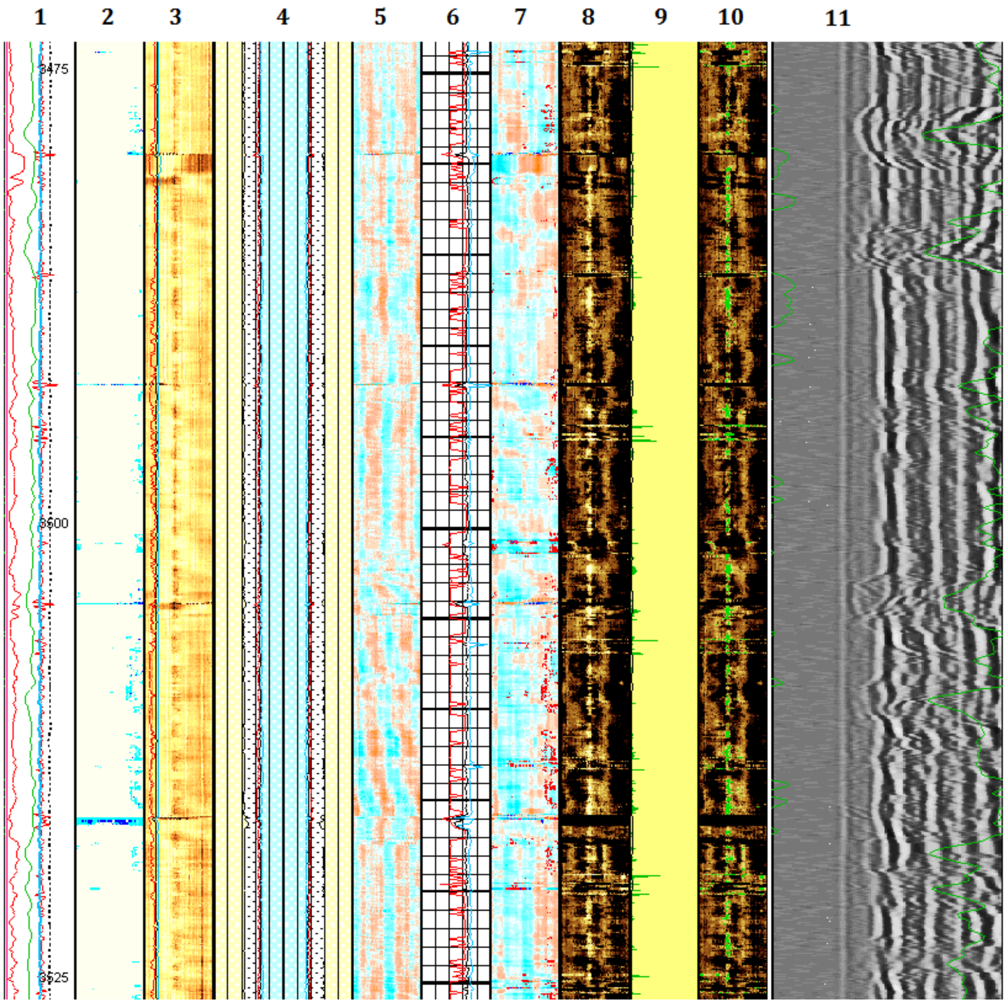

Figure 32: Well-bonded interval (section: 9-5/8" casing, interval: 3474mMD-3526mMD)

6.3 Case 3: Category 3

6.3.1 Case summary

This case has been categorized as a category-3 job because of uncertainty in the interpretation throughout most of the logged interval. More specifically, the log shows a low side channel over most of the section, but it is difficult to say whether it really is channeling or just a log artefact caused by improper casing cleanness. The log data are hence of such quality that it impairs the final certainty of cement evaluation and thus belongs to category 3. The 9-5/8” casing was set to 3050mMD and cemented in place with conventional 1.92 SG slurry (*CMT Type B*) with theoretical TOC at 2200mMD and 2500mMD for the tail and lead cement, respectively. No losses observed during cementing. Max deviation of the section is 72 degrees from the vertical, and the previous casing shoe is at 1890mMD. The section was logged approximately 3 days after the cement job with a combined USIT/CBL in oil based drilling mud with a density of 1.43 SG. The log yield somewhat fluctuating results with alternate likely and unlikely isolation capacity. Presence of a channel on the low side might be a log artefact over some parts caused by debris inside the casing. However, it is difficult to say for sure which impair final interpretation.

6.3.2 Data quality check

The USIT generally exceed the recommended maximum level of tool eccentricity over several minor intervals for the logged section which is unfortunate to overall data quality, but not considered crucial. First echo amplitude is consistent but somewhat affected by the tool eccentricity (light and dark bands in track 3). In addition to tool eccentricity effects the amplitude map shows signs of lower amplitude recordings at the low side of the casing (dark colors) which can be caused by debris (mud or cement) inside the casing. Else, the USIT data quality is considered to be good. The CBL/VDL data are generally of better quality than the USIT data and reads expected values for transit time and free pipe amplitude.

6.3.3 Sections of interest

Poor USIT data, low side channel vs debris inside casing (2733mMD-2877mMD)

Figure 33 shows a section of the logged interval from 2733mMD to 2877mMD. The CBL amplitude curve (plotted in the bond index track) is mostly low, and while the VDL shows attenuated casing signal, which both suggest good bond condition for this interval. The impedance map displays general high impedance material but with elements of lower impedance material on the low side of the casing. It appears to be de-bonded solids on the low side of the pipe which is indicated by green color on the second to last track, which suggests a low side channel to be present. However, the narrow pattern seen in both impedance tracks correlates with low side debris inside the casing, which can be seen in the amplitude image in track 3. Debris inside the casing can cause the impedance values to read lower, what appear to be a low side channel can in fact be a log artefact. The issue continues with depth and will be discussed further in the next section of interest.

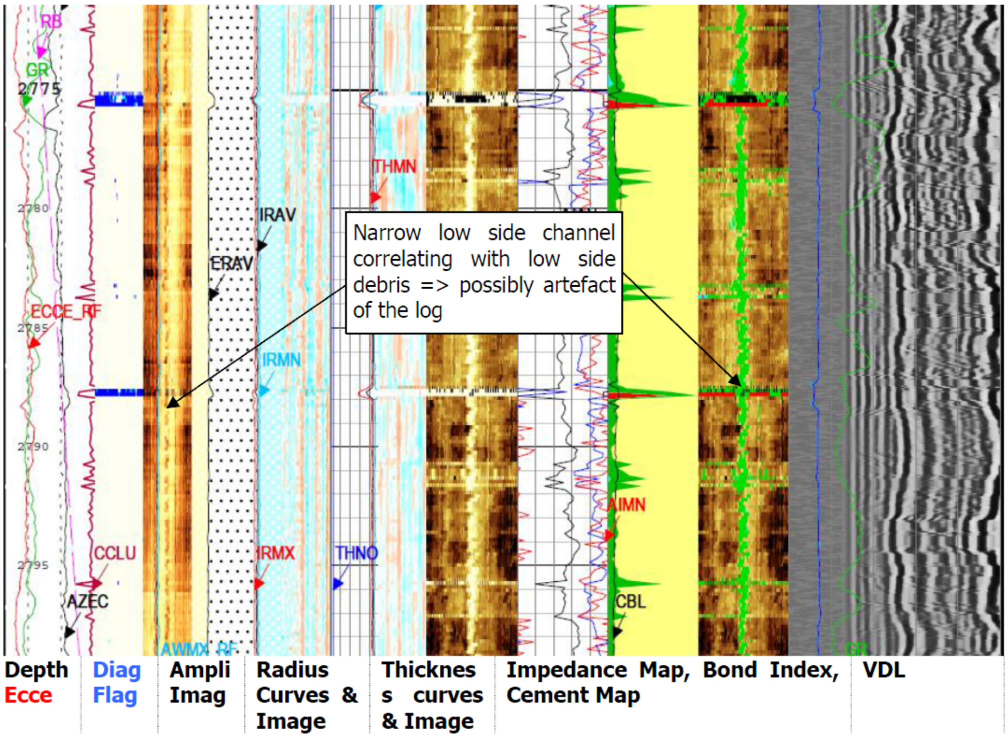

Figure 33: Impedance track indicates narrow channel, most likely log artefact(section: 9-5/8" casing, interval: 2733mMD-2877mMD)

Poor USIT data, low side channel vs debris inside casing (2877mMD-2932mMD)

Figure 34 shows a section immediately below the previous one, more specifically from 2877mMD to 2932mMD. The channel still correlates to debris inside the casing and is here also indicated by some diagnostic (processing) flags in track 2 and as dark color on the amplitude image in track 3. The red eccentricity curve in track 1 fluctuates, as mentioned under *Data quality check*, while the tracks showing radius and casing thickness generally have good consistency. The VDL in the far right track has diminished casing arrivals and the presence of formation arrivals which both indicate good cement bond. This interval hence look similar to the one above except from the increased width of de-bonded material on the low side, as indicated by more light color on the impedance map, and more green color on the bond index track. Even though the channel still correlates to the debris inside the casing, the width of it on the impedance map seems too prominent compared to the amount of debris indicated by the amplitude image. If the channel is real there will not be sufficient isolation capacity over this interval which is unfortunate to the success of the cement job. On the other hand, if the channel is in fact created by internal debris the cement quality will be too pessimistically evaluated. The problem, however, is that it is no good way to tell if the low side channel is real or it is a log artefact for sure unless an attempt to clean the inside of the casing is done prior to a second log run. Whether or not a more skilled person is able to see when the debris is responsible for such low-side de-bonding and when it is not, it should still be stressed how important it is to make sure the casing is properly cleaned prior to the logging operation. Such uncertainties should be avoided so that the cement can be interpreted with confidence and so that more trust can be put in the final result.

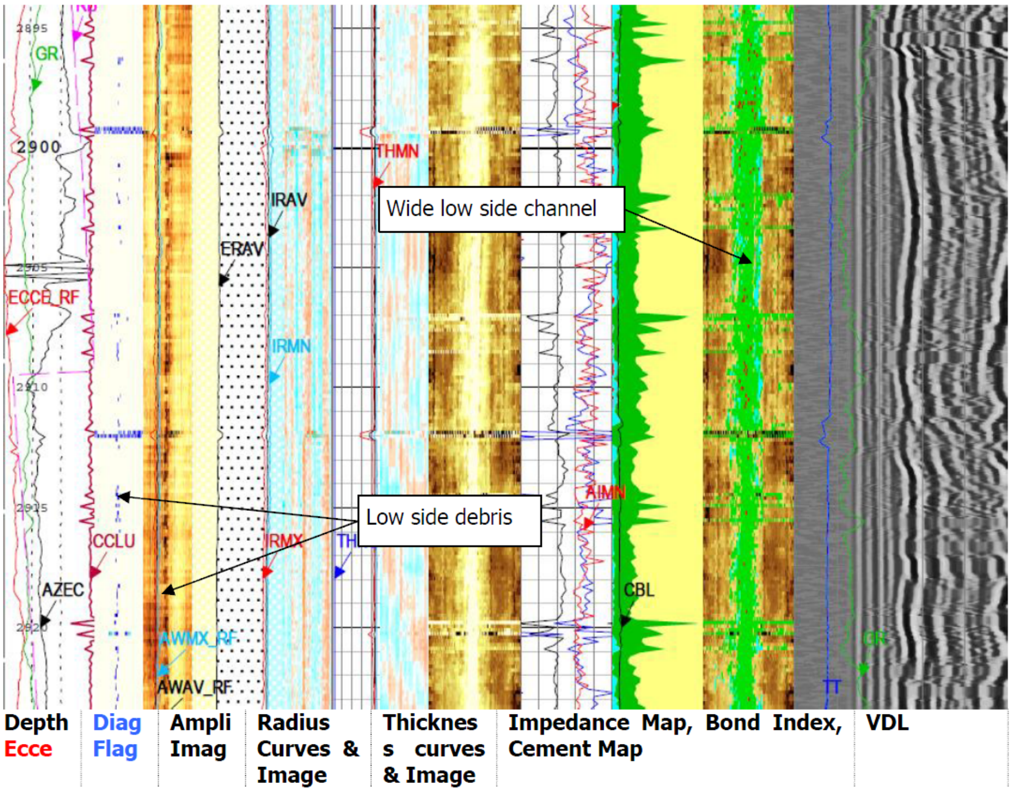

Figure 34: Impedance track indicates wide channel, difficult to tell if log artefact(section: 9-5/8" casing, interval: 2877mMD-2932mMD)

6.4 Case 4: Category 4

6.4.1 Case summary

The involved cases in this section are extracted from the same well, where both the production casing and production liner are considered a category-4 case. Because both jobs were logged by the same log run they share logging parameters and data quality check and are hence jointly presented as case 4.

The 9-7/8” production casing was cemented at time zero while the 5-1/2” liner was cemented in place approximately one and a half month later. For the 9-7/8” production casing, an expanding cement slurry (*CMT Type D*) was used while the 5-1/2” liner was cemented in place using a different slurry design (*CMT Type C*). The production casing was set at 3570mMD while the production liner was set from 3468m to 4427mMD, leaving a liner lap of about 100 meters. Hydraulic simulations for the 5-1/2” liner show TOC at 3283mMD, almost 300 meters above the previous casing shoe. Maximum well deviation is equal to 63°and 94°for the 9-7/8" casing and the 5-1/2" liner, respectively.

The 9-7/8" casing was logged for over 700 meters from 3461mMD to 2755mMD while the 5-1/2" liner was logged for about 900 meters from 4375mMD to 3468mMD. The first log run shows poorly circumferential coverage of the 9-7/8” casing, while the second run (two months later) is indicative of some improvement. For the 5-1/2" liner the second run shows moderate to poor circumferential coverage of the pipe for most of the interval. Note that the second run referred to for this case is the first (and only) logging run for the 5-1/2” liner. Weight is given on qualitative interpretation of data from the second log run which include both sonic (CBL) and ultrasonic (CAST) log data. There is also a brief comparison of data from the first and the second logrun for of the 9-7/8" casing to demonstrate improved bond conditions.

6.4.2 Data quality check

Quality checks are carried out to validate the response of the CBL tool. Casing parameters such as ID, OD, and weight are used to arrive at expected response values for the specific casing, while a free pipe logging pass is run to check the actual response. The CAST tool does not require to be calibrated by such pre-job free pipe pass due to its self-calibrating style of measurement and processing methodology.

Expected response together with actual tool response in the 9-7/8” (66.9 lb/ft) production casing are given in the below table to illustrate the principle of tool calibration. Actual response of the tool in this case was obtained from an approximately 100-meter free pipe pass (from 1255 to 1362 mMD), which is shown in Figure 35. The first track shows the transit time recorded at the 3-foot receiver on a scale from 402 to 302 microseconds. The curve is nice and smooth with only a small increase at each collar, which is natural due to small fluid gaps. Track 2 shows the amplitude recorded at the 3-foot receiver on a scale from 0 to 100 millivolts. The amplitude curve appears as a nice and smooth line around 50mV with only a minor decrease of about 15mV at each collar. This decrease in amplitude is caused by the same fluid gaps that cause the TT to increase. Track 3 shows the MSG waveform recorded at the 5-foot receiver. The pronounced, straight “railroad-tracks” with strong casing arrivals and no formation arrivals concur with the characteristic CBL response of a free pipe section. One can also see minor disturbances in the waveform at each collar, commonly referred to as ‘chevron patterns’ or simply ‘chevrons’, which also are indicative of free pipe. Finally, there is a nice horizontal correlation of the chevron patterns from the TT curve, the amplitude curve, and the MSG waveform.

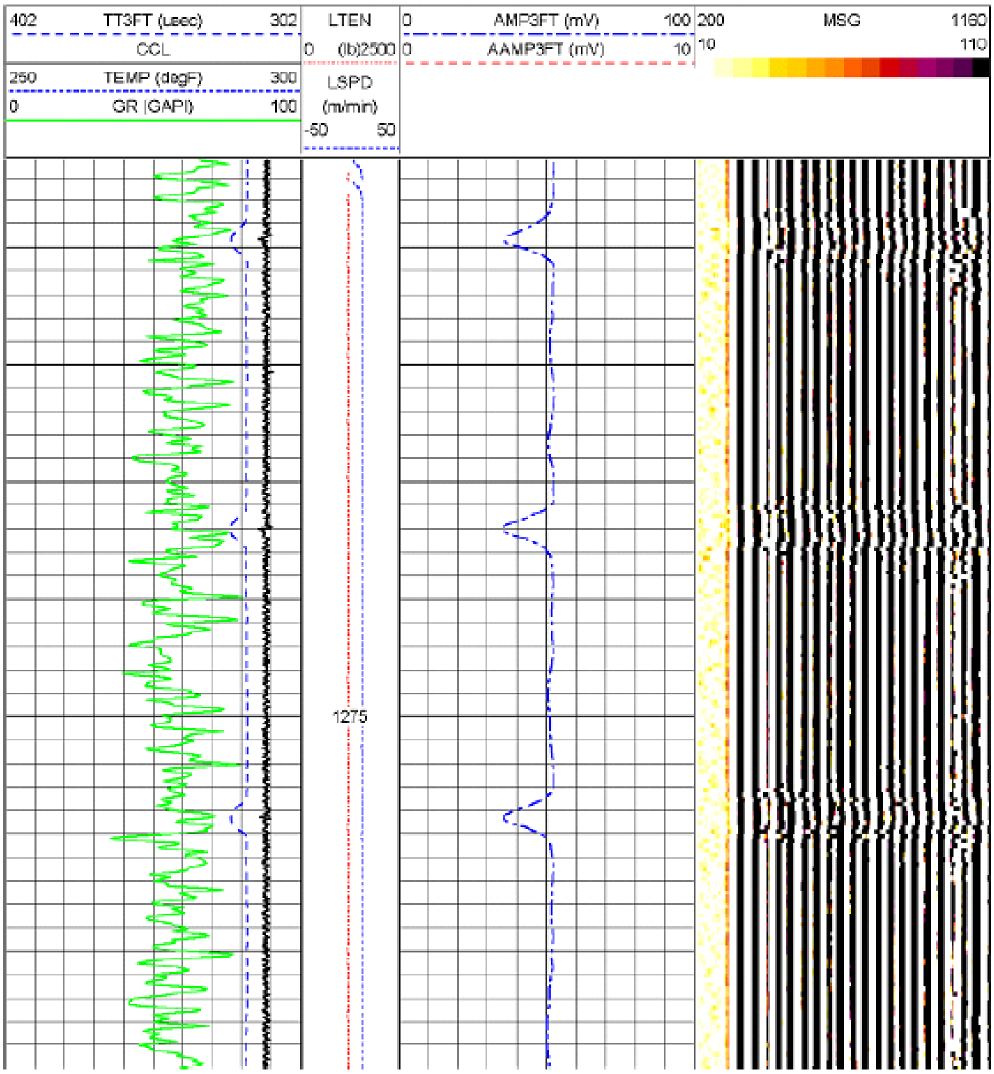

Figure 35: Pre-job logging pass of free pipe section to validate tool response

Table 7: Quality check of logging tool

Curve	Expected Response	Actual Response (from *free pipe* pass)
Travel Time in Free Pipe Section	322 [us/ft]	avg. 321 [us/ft]
Amplitude in Free Pipe Section	50.5 [mV]	avg. 50.3 [mV]
Internal Radius	4.2695 [inches]	approx. 4,3 [inches]
Outer Diameter (OD)	9,875 [inches]	approx. 9.8 [inches]
Travel Time in Fluid	180-260 [us/ft]	approx. 195-205 [us/ft]
Eccentricity	<0.15	avg. 0.04

6.4.3 Sections of Interest: 9-7/8" casing

9-7/8" Casing: TOC (2833mMD)

Figure 36 shows the logged interval were TOC for the 9-7/8" casing is found to be based on impedance data in track 5. The CBL waveform data in track 3 shows little variation and casing signal is still visible, so it is far form solid bond around the pipe. The TOC can, however, be spotted in the CBL waveform by how the sharp black-white transitions are weakened and appear more shaded with orange color below 2837mMD. The amplitude curve in track 2 experience a minor decrease from a steady 40mV down to 20-30mV over the same interval and track data thus correlate well.

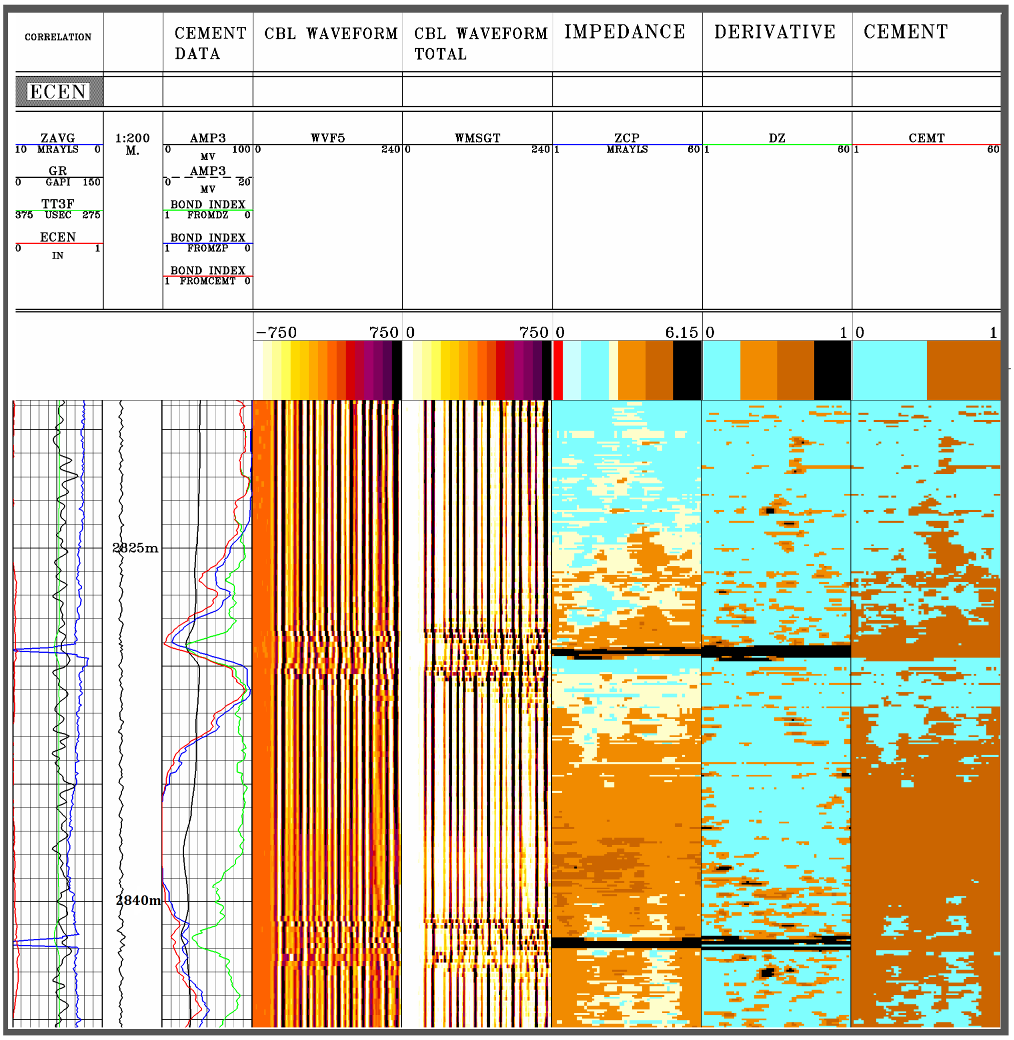

Figure 36: TOC at 2833mMD from 2nd CBL-CAST run (section: 9-7/8", interval: 2820mMD-2845mMD

9-7/8" Casing: 'Best' Interval (3247mMD-3261mMD)

Figure 37 shows an interval of the 9-7/8" casing taken from the second log run where the best cement sheath conditions are found to be. Starting from left in track 1, the red eccentricity curve plotted on a scale from zero to one is barely visible in the left margin due to generally low values (close to zero). The green transit time (TT) curve appear as a straight line with changes only at each collar, which is indicative of good tool centralization and thus the reason for the low-lying eccentricity curve. The black amplitude curve in track 2 decreases from 30 mV to 10 mV around 3247mMD and continues to stay low down to around 3261mMD. Over this very same interval the CBL waveform data in track 3 appear attenuated with barely visible casing arrivals. The dominant color for the interval is equal to the color in the middle of the scale for the CBL waveform (orange), i.e. around zero which indicates attenuated signal (as opposed to black-and-white alternation which indicates free pipe). There is also possible to see traces of formation signals further back in time; that is the irregularities or squiggles that can be spotted towards the right in track 3. The squiggles reflect inconsistent measurements with depth which are caused by lithology changes and thus an indication of formation arrivals. Track 4 contains the WMSGT (CBL Total) which is the combined presentation of the variance of the input WMSG and the WMSG (i.e. WMSGT = WMSG+WMSGD). The impedance map in track 5 is extracted from the segmented curves of the ultrasonic CAST tool. The black and brown colors indicate high impedance material in the annulus (cement indicative) and thus agree with the amplitude and waveform data of the CBL. The derivative in track 6 represents subtle changes in impedance values, i.e. a homogenous material like fluids are indicated by light colors while the more heterogeneous cement are made brown to dark. Note that because homogenous cement may appear as a fluid on the derivative map it is necessary to jointly approach all data in order to get an adequate interpretation basis. Track 7 is a final cement map based on the two previous tracks; if either one of the impedance map or the derivative map indicate cement (or both), the cement map will indicate cement by giving it a brown color. If neither of the two tracks indicates cement, the cement map will indicate fluid (blue color). Overall the amplitude and the waveform data from the CBL correlate nicely with the impedance data from the CAST for this segment, and for the rest of the logged section.

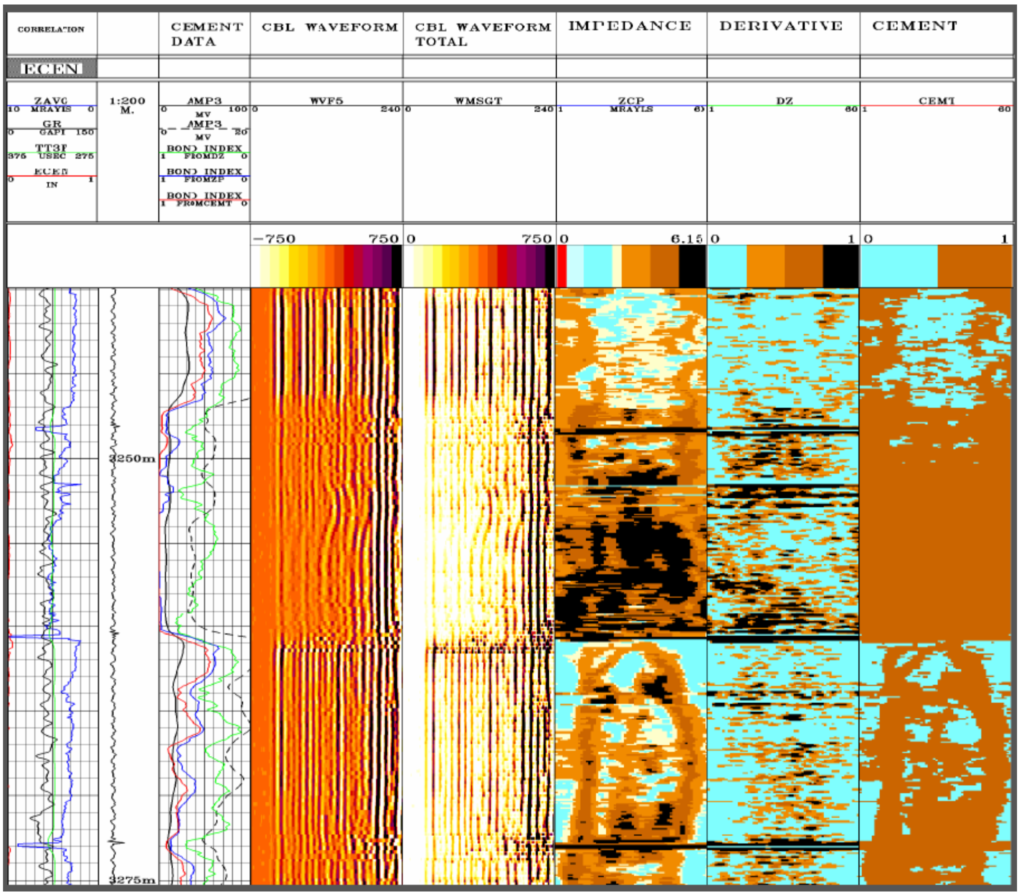

Figure 37: Good interval taken from the 2nd CBL-CAST run (section: 9-7/8", interval: 3240mMD-3275mMD

6.4.4 Data comparison 9-7/8" casing: first and second log run

Average amplitude

The 9-7/8" production casing is the only section for this well that has been re-logged after a significant period of time. It is hence natural to compare the data from the two logging passes to see if cement sheath evaluation is subject to any change. By quantitatively comparing average amplitude values over segmented intervals of the pipe, there was a rather clear indication of improvement with time.

The plot in Figure 38 clearly illustrate how the recorded amplitude at the 3-foot receiver has decreased from the first to the second log run. Decreased amplitude is indicative of better bonding around the pipe and thus improved cement sheath quality. The plot also shows how the trends of each data set follow each other closely which suggests good correlation between the two logging runs, i.e. the intervals with decreasing amplitude trend in the first run have the same decreasing tendency in the second run, only with lower values (like the interval between 2835mMD-2935mMD). The trend resemblance can as mentioned be seen as a quality element for the logging tool as opposite trends would have been more difficult to account for. However, it is far from an absolute quality measure as the tool can have been subject to the same error or shortcoming during both runs. Note that the interval from 3355mMD to 3455mMD is more heavily plotted for the first run compared to the second run and thus shows a more frequently change in amplitude. Despite this, a resembling (decreasing) trend can still be spotted for both data sets.

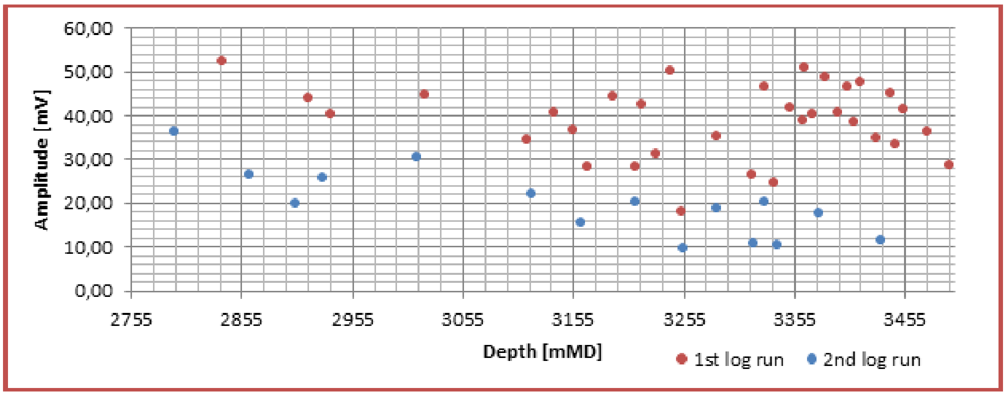

Figure 38: Recorded (average) amplitude values for the 9-7/8" section

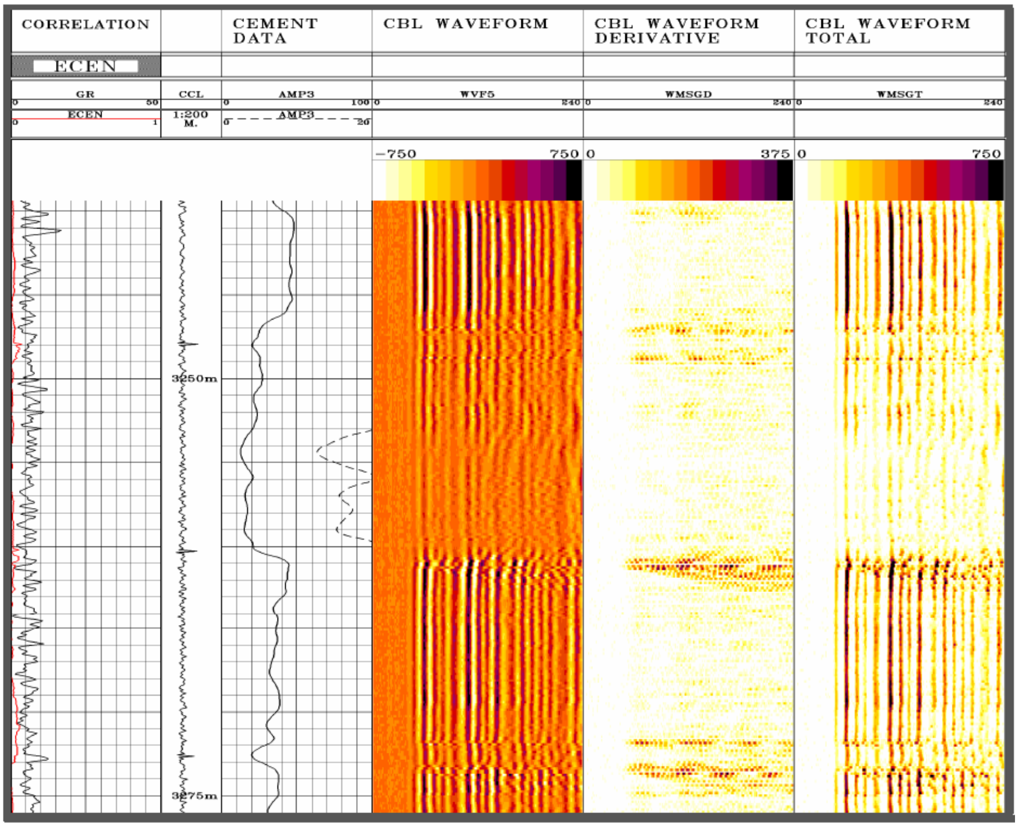

Figure 39: CBL segment from first log run

The 'best' interval (3247mMD-3261mMD)

Interpretation of log data from the first run also suggests that the interval from 3247mMD to 3261mMD is the one with the best circumferential coverage and bond. The interval is shown in Figure 39 and track 2 contains the amplitude curve. Similar to the 2nd log run, the interval starts with a rather distinct amplitude decrease and ends with an equally evident amplitude increase. The absolute values are generally higher in the first run (from almost 50mV, down to around 20mV, then up to around 40-45mV), but the relative change compared to the second run is in any case similar, with 60% and 66%, respectively. Observations are in accordance with the overall decrease in amplitude, as revealed by the plot in Figure 38.

6.4.5 Sections of Interest: 5-1/2" Liner"

5-1/2" liner: TOC (3488mMD)

The logging pass for the 5-1/2” stretches from 3475mMD to 4330mMD where the first signs of cement are seen at 3488mMD, as shown in Figure 40. The segment above 3488mMD is deemed insufficient for cement evaluation due to a connection at top of the liner. The log over this short interval (3475mMD-3488mMD) shows a fluctuating TT curve in track 1 and irregular spikes in the CCL. The amplitude is also very low (close to zero) and the CBL waveform data shows nearly full attenuation, simultaneously as the CAST data in track 5 shows very low impedance values that indicate gas or fluid in the annular space. It is correct to consider this as invalid data and to conclude that this is not the real situation down hole. Regarding the suggested TOC, it is primarily the impedance data (track 5) which is indicative of cement as the waveform data of the CBL show strong casing signal and no formation arrivals. It is overall a difficult area to interpret due to the existing transition from invalid data to valid data indicative of cement. The impedance data in track 5 is the final presentation based on the five impedance curves from each of the nine segments of the borehole, giving a total of 45 curves. The segmented curves shown in Figure 41 lack correspondence across the segments over the first 10-15 meters, but seem to stabilize and coincide more past the point around 3488mMD. This supports the judgement of invalid data above 3488mMD.

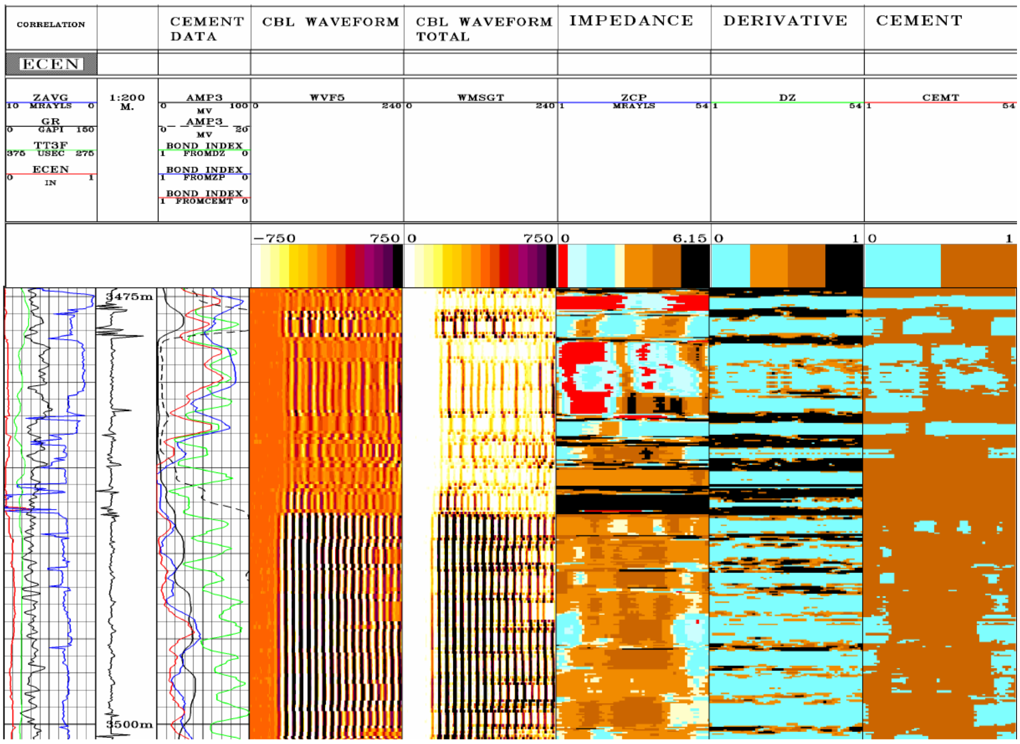

Figure 40: Suggested TOC around 3488mMD (section: 5-1/2", interval: 3475mMD-3500mMD)

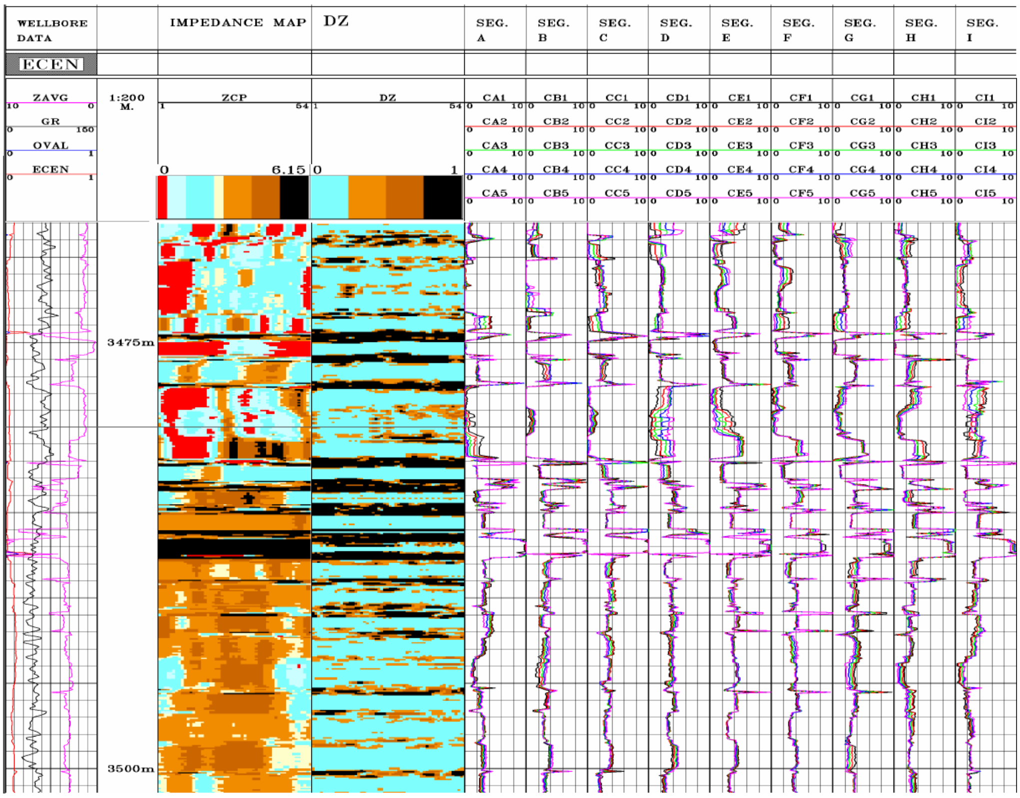

Figure 41: Segmented curve presentation of suggested TOC (section: 5-1/2", interval: 3460mMD-3530mMD)

5-1/2" Liner: Partially Bonded Interval (3725mMD-3798mMD)

Figure 42 shows a near 75m long section of the 5-1/2" liner with mostly partial bonding conditions (similar heading and scales as the log presentation in Figure 40). Starting with track 1, the eccentricity curve is more fluctuating and more high-lying than for the previous casing section (around 0.1), yet it is still considered to be within acceptable limits over this interval (<0.2). The amplitude curve (track 2) fluctuates between 30mV at the highest down to almost 10mV at lowest. The waveform data (track 3) reveal poor bonding to pipe over (almost) the entire interval, typically caused by a microannulus. There are strong casing arrivals which means that the pipe is ringing, which again means that there is no good circumferential cement coverage of the pipe to dampen the acoustic signal (remember the bell's ring). Recorded signals received later in time appear more attenuated so there is dampening material present in the annulus. Track 5 contains the impedance data which may seem indicative of circumferential coverage, but is in fact not. The impedance value of the cement over this interval is lower than what has been derived from UCA test data and is therefore not to consider as a good bond interval. However, during log interpretation, it is important to keep in mind that impedance values from CAST data are calculated based on measured amplitude and that it will therefore be affected by how the cement to casing bond is (which is the whole purpose). Hence, the impedance data from ultrasonic logs will generally not be in accordance with the UCA test data, and this particular issue will be approached later in section *7.0 Discussion*. So, based on this qualitatively interpretation the interval is mostly described as partially bonded with poor circumferential coverage. There are, however, minor zones with decreased amplitude and less visible casing arrivals which indicate better bonding to the pipe. Two of these zones are framed with red and enlarged in Figure 43 and 44 on page 72.

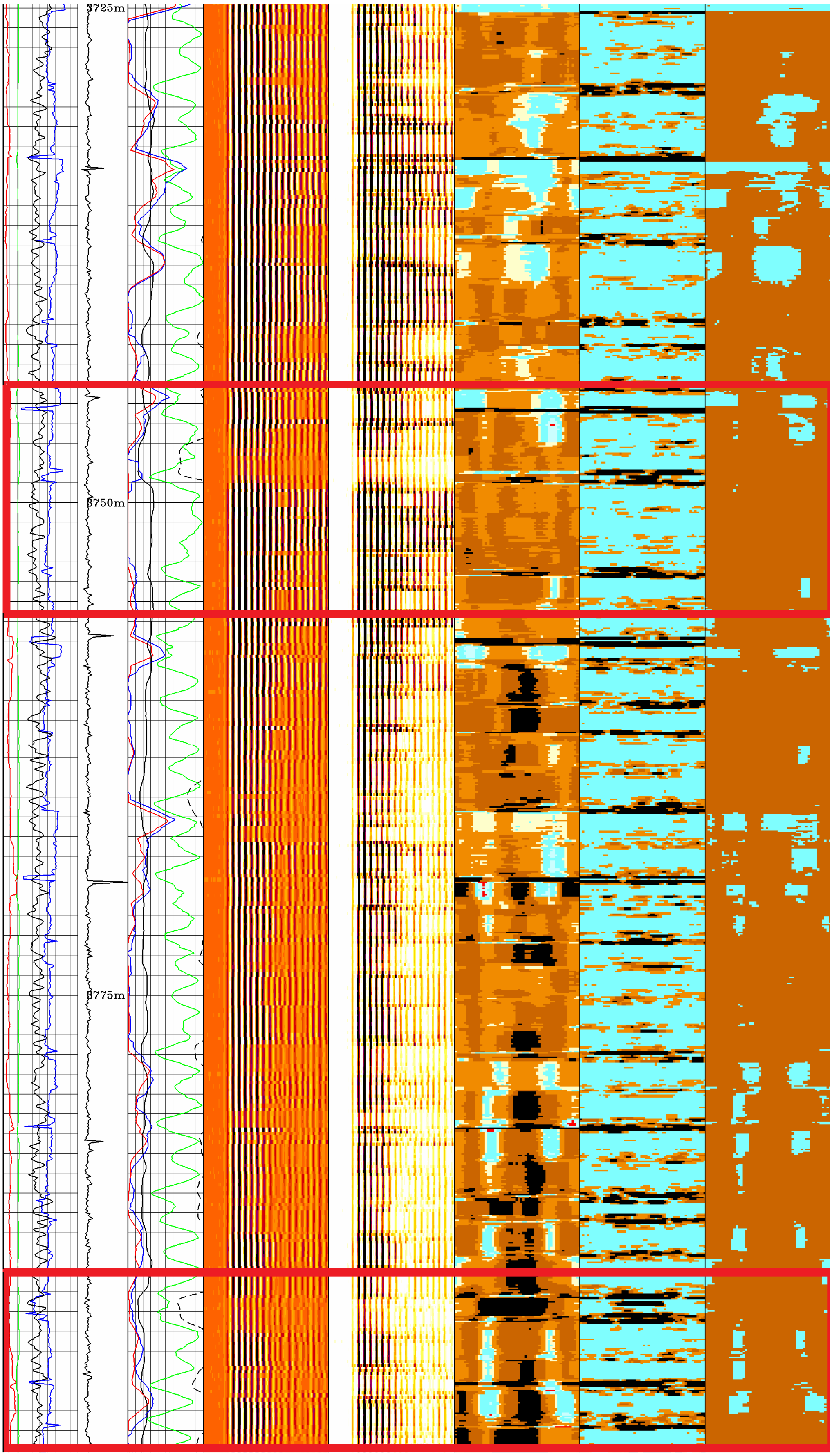

Figure 42: Large interval from 3725mMD-3798mMD (section: 5-1/2")

For both zones there is a decrease in amplitude down to almost 10mV which corresponds to less visible casing signals in the waveform data. In zone 1 (Figure 43) the bond improvement is visible from 3747mMD to 3749mMD, while in zone 2 (Figure 44) the improved bond goes from 3790mMD to 3792mMD. The impedance data (track 5) shows good circumferential coverage for the same zones and hence the data correlate nicely which in turn gives reason to believe that the bond is in fact better over these short intervals. Both TT and eccentricity curves (track 1) appear to be fine with respect to tool quality so the data appear accurate.

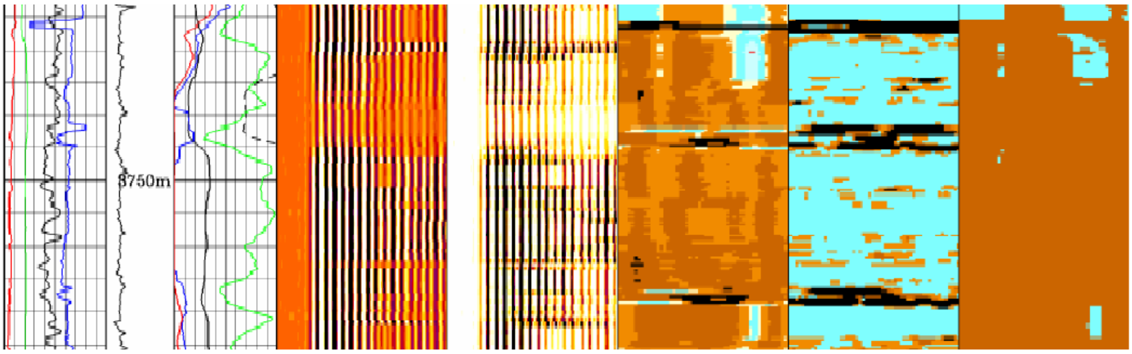

Figure 43: Zone 1 with improved bond condition (section: 5-1/2", interval: 3745mMD-3755mMD)

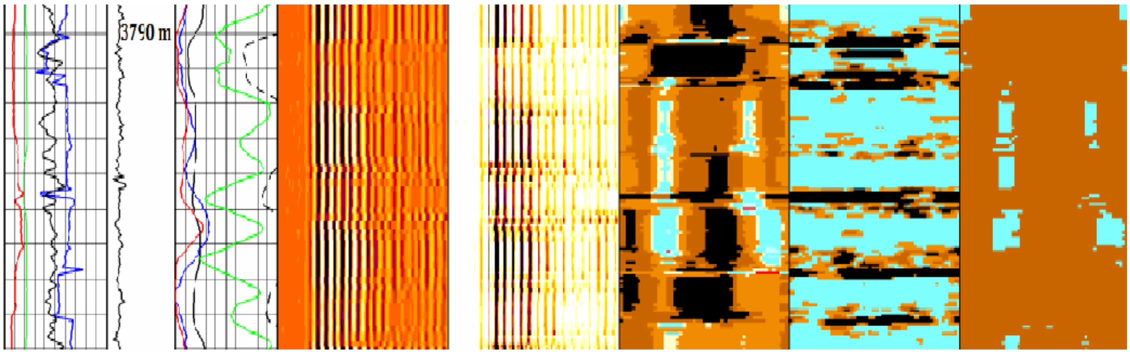

Figure 44: Zone 2 with improved bond condition (section: 5-1/2", interval: 3790mMD-3800mMD)

5-1/2" Liner: Eccentricity Problems (4020mMD-4040mMD)

The selected log interval in Figure 45 suffers from too high eccentricity values. Whenever the eccentricity curve exceeds the recommended value of 0.2 (scale from 0 to 1) a grey shading is applied to the exceeded area. The eccentricity has a rather clear effect on the calculated impedance, as seen by the red areas in track 5. The overlapping red and black areas indicate the presence of very low impedance material (like gas) right next to high impedance material (cement), which is not the real case for the well. The phenomenon is the same as was illustrated by Figure 15 on page 34, but with green color instead of red. The incorrect display is due to tool eccentricity and that the impedance calculations are based on the wrong portion of the waveform, as discussed in section4.7.4. There is also intervals above (3915mMD-3970mMD) and below (4040mMD-4060mMD) subject to similar tool eccentric effects.

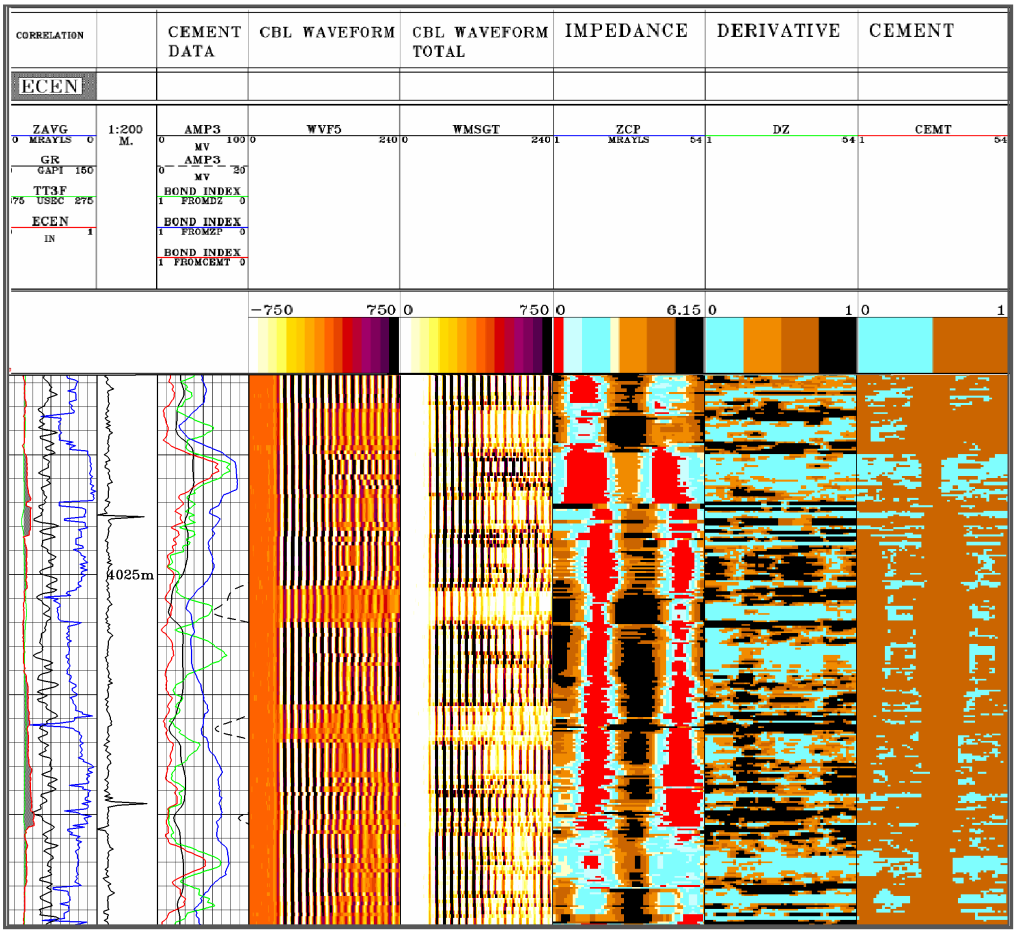

Figure 45: Interval with eccentricity problems from the 2nd CBL-CAST run (section: 5-1/2", interval: 4020mMD-4040mMD)

6.4.6 Case comments

Overall, the cement evaluation logs exhibits poor circumferential coverage of the 9-7/8" casing. Smaller intervals with moderate bonding are found for the 9-7/8" production casing, but the overall interpretation is in any case not convincing. The interesting part is the observed decrease in average amplitude values between the two log runs. The change in recorded amplitude suggests that the cement bond has improved with time which might be because the cement has been given more time to cure and build compressive strength, or the cement has expanded and become better bonded to the casing. This being said, the cement was given about 10 days to cure prior to the first log run, which should be sufficient according to the UCA test. Based on this it is not safe to say whether the UCA test or the logging tools are providing inaccurate results, or if the slurry behavior down hole is not understood properly. Contamination of the cement can be an additional cause. For the 5-1/2" liner section there is a strong indication of microannulus for most of the interval but there is unfortunately no pressure pass available to better confirm the presence of it.

Adjacent wells have been drilled and cemented in similar manner but because they have not been logged yet, there is not sufficient data available to make any further conclusions at this point in time. However, it will be interesting to check future log data from adjacent wells and look for resembling observations.

6.5 Case 5: Category 4

6.5.1 Case summary

This case is included with respect to logs ability to adequately measure the cement bond at various times. Several cases are observed to yield improved log result when re-logged later in time. For this case, the interval of interest has in addition been re-logged later in time using a different input value for cement compressive strength. Slight improvement in cement bond is observed from first to second run where compressive strength input is equal to 2000psi, while the third run with an input value of 4000psi and executed almost one month later, shows a significant decrease in bond quality. The tool string used for all log runs consists of SBT/VDL. The observations underline the importance of approaching data together during log interpretation including input parameters with significant effect on data presentation. The full length of each log is not included, but a small (yet representative) 12-meter segment from each of the three log presentations are given in Figures 46, 47, and 48 and will be referred to as log 1, log 2, and log 3, respectively. The 12-meter intervals contain the part of the logged section where the best cement bond is found to be (3875mMD-3879mMD).

6.5.2 Sections of interest

First of all, when directly comparing log results, it is important to make note of the scales for the different presentations to avoid any misconceptions. The GR in track 1 are plotted on a scale from 0-100 for log 1 and 2, while log 3 has it on a scale from 0-150. So, even though the GR curve appears to be 'lower' for log 3, it is still reading the same as the two previous runs (about 30). Apart from the GR curve, all other scales are the same for all three presentations including depth, so the data presentation allows directly comparing with the exception of a higher cement strength value for log 3. Further, the TT curve (track1) appears as a straight curve with only deflection at the collar which is a good with respect to eccentricity and tool quality.

From log 1 to log 2 there is slight improvement in circumferential cement coverage which is seen by comparing the gaps between max (ATMX) and minimum (ATMN) attenuation rates (3875mMD-3883mMD). When annular material is homogenously spread around the pipe there will be little variations in attenuation between each radial segment and the curves will hence follow each other closely. Whenever there is an uneven distribution, like for instance a low side channel, the curves will separate from each other. The observed improvement is reproduced as more dark areas in the cement map in track 4. The waveform data (track5) shows weaker casing signals in log 2 which is indicative of a better bond to the casing. Overall, the second log carried out 2 days later than the first is indicative of improved cement bond.

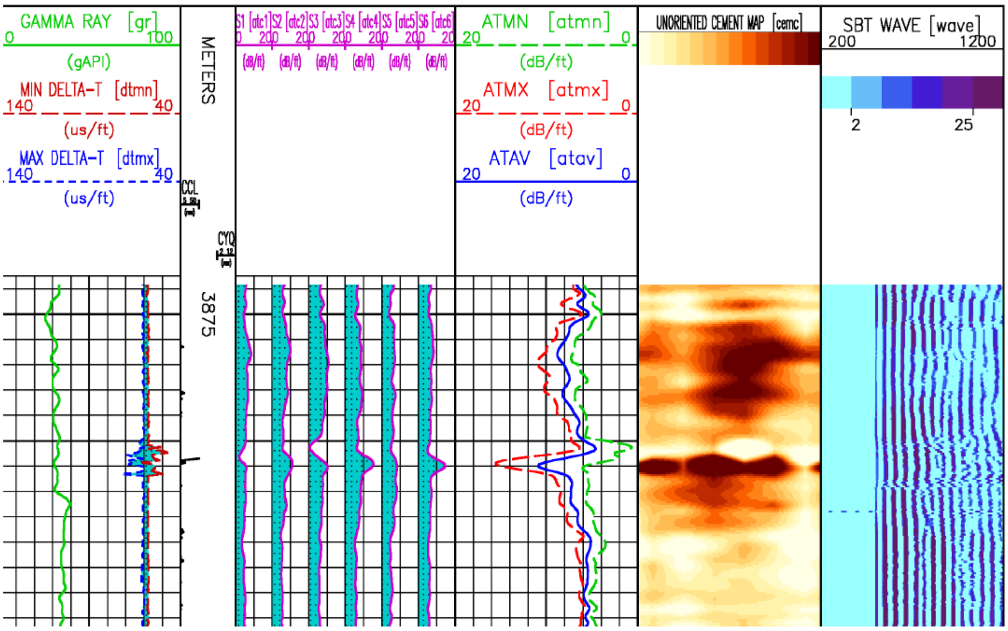

Figure 46: Log 1(section: 9-5/8" liner, interval: 3875mMD-3887mMD)

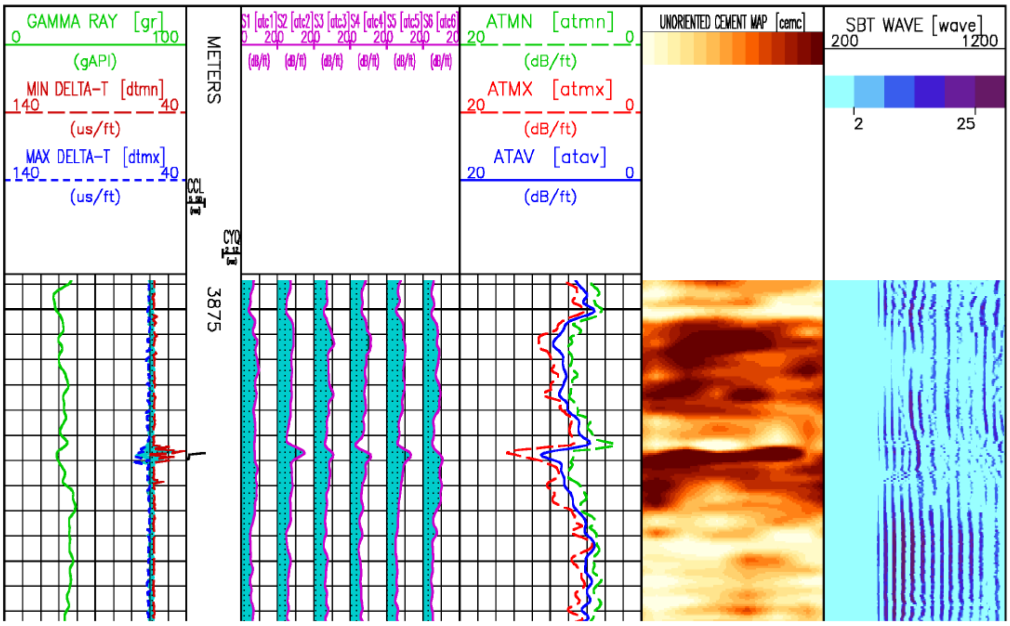

Figure 47: Log 2(section: 9-5/8" liner, interval: 3875mMD-3887mMD)

Log 3 on the other hand indicates the opposite trend than log 2, i.e. a decreased bond quality with time. Log 3 in Figure 48 shows clear casing arrivals in the waveform data (track5) and generally lower attenuation rates with a resulting average around 6dB/ft, which is more than 2 units lower than for the first two logs reading about 8-9dB/ft. The selected compressive strength of 4000psi instead of 2000psi is a more pessimistic input value as it expect higher attenuation rates that consequently yields higher cut-off rates with respect to bond quality (hence more pessimistic).

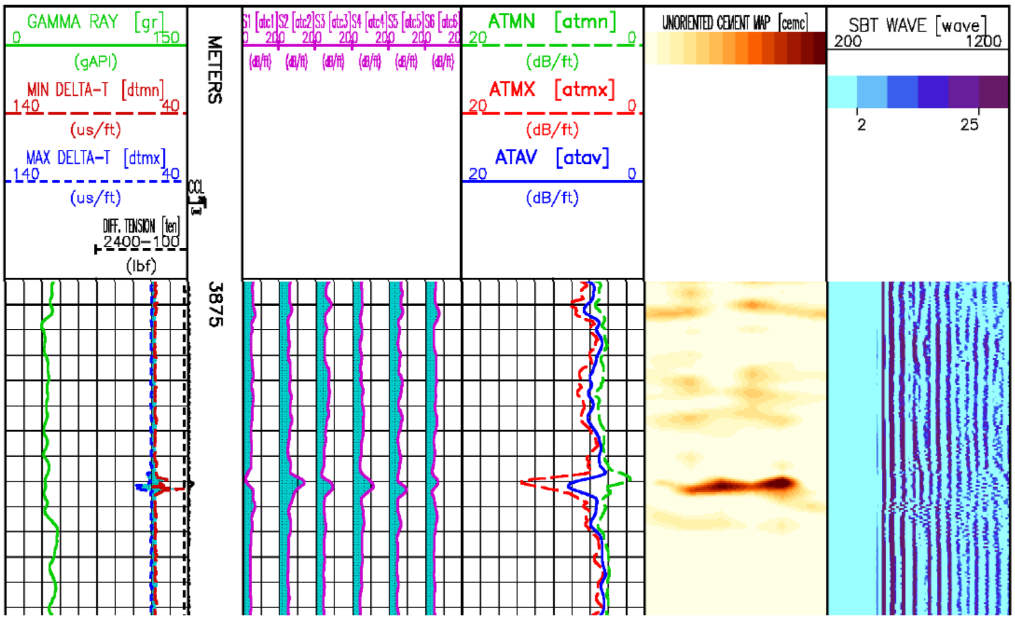

Figure 48: Log 3(section: 9-5/8" liner, interval: 3875mMD-3887mMD)

6.6 Summary

The objective of the case studies was to demonstrate the job-categorization used for the statistical survey. Characteristics of the selected cases are presented and together they constitute the argument for why each case is assigned to the particular category. No two cases will be exactly the same within one category, and the division process carried out is of qualitative and somewhat subjective character. The case studies should, however, provide a sufficient anchor point for the descriptions of each category which were given in *section 5.3*.

In addition, the case studies revealed how changes of multiple parameters between cases introduce further challenges to the troubleshooting process, like for instance how the two first cases (category 1 and 2) were logged with the USIT while case 4 (category 4) was logged with CAST. Further, the first two were conventional slurries while case 4 involved a non-conventional slurry (*CMT Type C* and *D*). Even further, the two first were logged in mud densities of 1.43 and 1.41 SG, respectively, while case 4 was logged in 1.73 SG. So, there are already three important parameters with plausible affection on the final cement evaluation that have changed among these cases. This challenge repeats itself in the statistical survey as well, and renders difficulty to finding any plausible explanation to the ultimate problem. This will, however, be discussed further in the following section.

7.0 Discussion

The process of assessing each case, including cement job execution, logging operation, and log interpretation, is based upon available data and knowledge obtained from job reports, log presentations, logging reports, course material, and input from fellow colleagues at Halliburton. Overall impression of each studied case will to a certain extent be of subjective character and results should be interpreted accordingly. The choice of including two intermediate categories was, however, done to mitigate the effect of this subjectivity and to arrange for a more conservative interpretation, which is possible by only include category 1 and 4 in subsequent evaluation of the results. The case assessment is further of qualitative character and there has not been assigned any particular cut-off values or similar to govern the case classification. A major reason for the latter is the complexity and amount of parameters included to each case which render difficult to the introduction of pre-determined cut-off values. To calculate the *total length of expected isolation given as a percentage of the planned cement column* is one method to assign a number to the success of a cementing job. Such quantitative measures have, however, not been approached in this thesis and care should in general be taken when assigning a single number to such a complex composition of elements. Consequently, this thesis has taken a rather broad approach to each case where the final categorization is based on the overall impression of the case. This approach is believed to be best suited for the problem at hand.

Complexity is a fundamental reason for the broad approach taken. The approach is believed to be more suitable for coping with the synergy at stake, as opposed to solely focusing on a few factors. This being said, a broad approach will on the other hand introduce a superficial tendency of which final results can be impaired by. In light of this, the author would like to emphasize that the primary objective of this thesis was to investigate any trend that could help explain discrepant results and other experienced problems. Data gathering, case assessment, and case categorization constitute the basis for the statistical survey included, which is believed to be sufficient for overview purposes. Any plausible pattern discovered must nevertheless be studied in more detail and be reproduced in a larger sample population before a more firm conclusion can be drawn.

The sample size of 38 jobs appears to be rather small with respect to the number of involved factors, which consequently imposes a significant degree of uncertainty to any finding. During research, the complexity to the problem appeared to be of more considerable character than first assumed, and unfortunately there was not feasible to include a larger sample size at the time. In light of this it is recommended that the survey proceeds in the future by continuously plotting operational parameters against each other to see if patterns will alter or remain, and eventually become clearer. Extending the survey will allow for more efficient data gathering in the future by encouraging involved personnel to contribute with specified data. All relevant data will be gathered in a much more efficient manner as compared to one individual digging up job papers and searching through databases to find information on jobs executed a couple of years back. Another benefit of performing the survey en route is the ability to be somewhat alerted whenever similar jobs are to be carried out, and then use these jobs (and others) to try and prove/disprove plausible theories. The author acknowledges that there will be great limitations to how freely one can adjust operational parameters on such basis alone, but it should still be mentioned as a general recommendation to do so, at least as long as the involved changes are considered feasible to the operation. Logging the same cemented casing with logging tools from different service companies would for instance provide very interesting knowledge to the investigation, but as far as the knowledge of this thesis goes, such project has not been carried out.

The chart in Figure 22 contains those operational factors which are believed most plausible to yield any pattern for further investigation. The strength of the chart is that it clearly displays the category distribution for each given factor which simplifies the search for one particular troublesome factor. The shortcoming of the chart is that all factors are presented independently so that the overview cannot be used to assess interrelations between factors and thus not how such interrelations might potentially affect the final job outcome. The issue reveals itself when an attempt to study the impact from one parameter is made, like for instance mud weight (density). Note that even though the mud weights in the survey are extracted from the logging operation, they will still to a large extent represent the mud weights used immediately ahead of, and during cementing. In any case, the two upper mud weight classes in the chart are largely subject to what has been classified as category-4 jobs, or more specifically, six out of seven *category-4* jobs involve high mud weights (>1.65 SG). The tendency is somewhat clear, and it is also common knowledge that heavy mud weights introduce challenges to both the logging tool and to the mud removal process prior to cementing, as discussed in previous sections. So, if the mud weight was the only value actually changing between the cases it would be reasonable to suggest mud weight as a plausible cause to experienced problems. However, alongside the change in mud weight there are also several other parameters that change, where some of them constitute the very reason for adjusting the mud weight at all. Mud design vary with wellbore conditions like temperature and pressure, and mud density is usually increased with depth to compensate for higher reservoir pressures, and thereby maintain well integrity. The slurry design and slurry density also tend to change with wellbore conditions and thus introduce, from a pure statistical view, yet another plausible factor to any plausible explanation. This being said, the case studies do also reveal problems associated with logging in high mud weights as well as problems with debris inside casing, which are residuals of either cement or drilling mud. In any case, the findings agree with the common view on how high mud weights impose challenges to cementing and cement evaluation. It should hence be one of the main focus areas for further surveying.

iCem® has proven itself to be powerful calculation tool for simulating different scenarios. The ability to produce a number of different graphs and charts together with visual two- and three-dimensional models, make iCem® highly applicable for post-job investigation. It should, however, be made clear that the program utilize calculations and assumptions that depend on chosen input values, so every model will be of theoretical character. Care should in general be taken when directly comparing theoretical models with actual job execution, but the strength of iCem® , however, is that it allows for several parameters and properties to be altered rather quickly so that several simulations can be run and assessed. The shortcomings of theoretical modeling can consequently be mitigated by computing worst-case and best-case scenarios.

Among the cases there are some that has been re-logged on a later occasion due to either request from customer, or due to an extension of the first logging run past a lower lying section. Regardless of purpose, most cases subject to re-logging are subject to alternating results between runs. In general there are signs of improvement (like case 4 on page 61), but some cases are also subject to minor setbacks with respect to cement quality (case 2 on page 54). Extended time for the cement to set up is usually considered favorably for subsequent log interpretation, as contamination of cement in the annulus might increase the actual set up time compared to the time derived from lab test results (UCA - Ultrasonic Cement Analyzer). The question to be answered is to what extent the real set-up time for the cement in the annulus can differ from UCA results, and if more time should be allocated before logging. Time is critical to the business because of very high operating costs, but there still has to be an adequate evaluation of the cement quality in place for the operation to continue. However, the survey results find no clear tendency with respect to elapsed time between cementing and logging. The of lack any tendency suggests that cases where time is believed to be a factor must be assessed individually and compared with jobs of similar character, especially non-conventional slurry designs with expanding properties.

In order to interpret a log correctly it is necessary to understand what data the log displays and how data are obtained. This includes that limitations related to the item being measured and the method it is measured by need to be understood so that wrongful interpretation of the data is avoided. As part of pre-job testing of cement design the slurry undergoes several laboratory tests including the mentioned UCA test which performs non-destructive compressive strength tests on cement slurry samples. Signal travel time (transit time) through the slurry specimen is also measured by the UCA and is used to calculate the acoustic impedance value for the cement. The test is conducted under pressures and temperatures selected to simulate the downhole well conditions where the cement eventually will be set to work. However, the UCA test is still carried out in a controlled lab environment, and the transit time is obtained from a different measurement technique than down hole. More specifically, the UCA measures *through* the medium while the CAST (and other ultrasonic tools) measures *reflections* of an acoustic signal that will be considerably affected by the acoustic coupling between the cement and the casing. So, if the coupling between cement and casing is perfect, the impedance values calculated by ultrasonic data should be close to the impedance values from the UCA, but in general it will be lower. A matter worth mentioning is also that the UCA tests are carried out on 'perfect' slurry samples whereas the cement downhole can be affected by the well conditions including loss to formation and contamination by spacer, mud and/or formation fluids. The degree of contamination will vary according to well conditions, like for a horizontal well without a bottom plug the cement will be more subject to spacer contamination. In light of this, general care should be taken when comparing impedance values derived from lab testing directly with the values obtained by downhole logging tools.

Tool problems and tool sensitivity have both revealed themselves as more widespread than first assumed, especially the USIT tool has appeared to become affected by mud conditions in the wellbore, including high densities while logging and residual debris on the internal casing surface. To what extent the mud condition affect the tool, and consequently the final cement evaluation, varies between the involved cases. For the cases assigned to category 2 the issues are believed to be of minor significance to the final interpretation, but for *category-3* cases the tool issues are found to impair the final work of cement evaluation. Log interpretation is a matter of assessing collected data, but if the data is subject to uncertainty, the final interpretation will be so as well. This being said, it should be mentioned that the case studies have demonstrated how poor data quality is discovered relatively easy, such as for the poor USIT data in case 2 and 3 (page 54 and 59, and the eccentricity problems in case 4 (page 61. The tools thus prove that they have rather good prerequisites for quality checks of the collected data so that invalid data can be left out of the interpretation. However, it is in any case unfortunate that supply of data to the cement evaluation process is reduced at all. In light of this, it should be emphasized on the importance of approaching *all* relevant data during cement evaluation such as, i.a., the physical properties of the cement and each tools ability (and sensitivity) to capture the presence of cement under varying conditions. The work process has to some degree indicated lack of sufficient communication between cement engineers and logging personnel, but this will not be discussed any further here due to lack of more adequate basis matter. What can be mentioned, however, is how the work with this thesis has underlined the complexity of cement evaluation, and it is thus safe to say that cooperation between cement engineers and logging personnel, both prior to and after job, can only be favorable with respect to the final outcome for the mutual customer.

As a whole, the statistical survey suggests rather few parameters to be responsible for why some of the cases suffer from more defiant results than the rest. On the contrary, a quick look at the study reveals a rather clear partition down the middle of the chart with only minor exceptions in between, which all together indicates a fairly random distribution. Among the exceptions, the most evident ones involve logging tool, mud density, cement type, and cement density. The same factors were addressed in the case study summary as they were all changing from the two first cases (category 1 and 2) to the more troublesome fourth case (category 4). All-together, this point towards one of them, or a combination of them, introduce troublesome challenges to the operation, but as argued before, the pattern should be reproduced in a larger sample population before any finite conclusion is made.

As mentioned, a major challenge with post-job investigation is the large number of plausible influencing factors and the fact that they will seldom be exactly the same from one job to the next. Well environment, slurry design, job execution, and tool design are some of the categories containing numerous parameters subject to some change. The result being that any particular factor(s) affecting the final correspondence between post-job evaluation and the job itself will be very difficult to reveal. Conclusions and plausible explanations can yet be drawn but will unfortunately be subject to a significant amount of uncertainty. Due to the extent of the problem and its costly consequence it should however be applied some effort to truly investigate troubled experiences and compare them with jobs of more fortunate results. Statistics far more comprehensive than included in this thesis should be run as a joint project between cementing company, logging company, and the operator. By continuously gathering data, store it in a database, and run crosschecks or other cunning algorithms with the ability to better reveal cases where common factors seem to be causing problems, will hopefully yield more firm conclusions. This thesis acknowledges the challenges of such collaboration but is at the same time certain about a composite solution involving factors from both cement and logging perspectives. Special physical properties of the slurry, irregular job executions, pre-job requirements, tool sensitivity, and more, should be confronted together to avoid mistrust in the final result. A challenge on the NCS is, however, that cement jobs performed by Halliburton are often logged by either Schlumberger or Baker Hughes, which complicates a jointly investigation.

8.0 Conclusions

The objective of this thesis was to look for any trending data that could help explain unexpected log results with respect to cement bond evaluation. The thesis has successfully confirmed the existence of poor job outcomes that lack sufficient explanation, and subsequent work found that a statistical survey based on individual case assessments was an applicable approach to the problem. The thesis was not able to find any finite explanation to the experienced problem, but related findings are summarized and included here.

The work found two particular factors to be more heavily involved in jobs with poor outcome, namely high density drilling fluids and a non-conventional cement type. Both factors appear to be troublesome for the logging operation and consequently to impair final cement evaluation. The factors were identified both statistically and individually, but the thesis lack sufficient details and an adequate sample size to be more determined on the impact from these two factors. The work suggests a more thorough study on logging operations involving the mentioned cement type and/or high density drilling fluids, and further to examine their presence in a larger sample size to see if they still stand out from the rest.

The thesis has found the problem to be of very complex character, mostly because of several factors that change between each job and consequently yield inconsistent job patterns that are difficult to compare. Because of the complexity, the sample size of 38 jobs is found to be too small to reveal evident patterns or to draw finite conclusions. The lack of finding evident data trends firstly suggests that there is little connection between involved factors and poor job outcome, but is in fact believed to be a result of the relative small sample size. The survey should hence continue in the future and data should be collected en route to arrange for appointed elimination of plausible trends and factors. Even though sample size is considered to be too small, the statistical approach in conjunction with case studies is found to be an applicable way to approach the problem at hand.

It has further been demonstrated how the software program iCem® can be applied to post-job investigations. By using input from an already executed cement job, job sequence including the expected cement displacement efficiency can be simulated. Input values can additionally be varied to account for uncertainties and to create best/worst case scenarios. Comparing several scenarios with the logging results are considered favorable to account for the theoretical character of the program.

Subjectivity will be present when qualitative case assessments are made. This thesis has demonstrated that intermediate divisions can be applied to such survey, so that cases found to be in an uncertain transition zone can be separated from the evident and more certain ones. This allows for a conservative interpretation of the data and thus mitigates the impact of subjectivity.

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